An Inventory Model with Recovery and Periodic Delivery that Considers Carbon Emission Cost

Ivan Yeo(✉)

Department of Mathematical and Actuarial Sciences, Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Kampar, Perak, Malaysia
yeohg@utar.edu.my

Abstract. This paper proposes an integrated inventory model that considers three types of inventories: used items, service items, and raw materials. Used items are collected from the market and are restored to a serviceable condition to satisfy demand. If the quantity of the restored items is lacking, then the remaining demand is satisfied by converting raw materials into service items through a production run. Demand is satisfied by shipping periodically in batches of equal size. The warehousing of items incurs a carbon emission cost in addition to the traditional holding costs. Additionally, the transportation of items to the client incurs a carbon emission cost as well. The objective of the model is to provide insights to help determine both the frequency and the size of the batch shipments to minimize the joint total inventory cost and carbon emission cost. This paper also proposes a numerical solution procedure and provides a numerical example to illustrate the model. A numerical sensitivity analysis is performed to derive insights that are potentially beneficial to policy makers.

Keywords: Inventory model · recovery · periodic delivery · carbon emission cost

1 Introduction

Rapid global industrialization has given rise to environmental, climate, and energy challenges. It is believed that the excessive emissions of greenhouse gasses (GHGs), especially carbon, is a major cause of climate change [1]. Recently, regulators have started to deal with the GHGs emissions problem by introducing regulations and policies such as the EU Emission Trading System (ETS), the carbon emissions allowance scheme for power plants in the US, and the carbon taxation scheme in Australia [2]. However, industry players are still reluctant to prioritize carbon emissions reduction over profitability; as such, understanding how to achieve the former while preserving the latter has become a critical challenge [3]. Moreover, the focus of the responses to the regulations and policies has been to adopt more energy efficient technologies. The fact that the industry players may reduce their carbon emissions by optimizing their decisions in production, inventory, and transportation, often at little to no cost, is largely missed [4]. Furthermore, in addition to optimizing management decisions, the industry players may also optimize the collection and recovery of used items (see for example [5]).

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In [5], a three-stage supply chain that consists of three actors–a final product manufacturer, a component manufacturer, and a used component collector–is considered. The authors considered three sustainability factors–recycling of used components, carbon emissions control, and transportation costs of JIT (just-in-time) deliveries–and investigated both the classical policy of not implementing carbon emissions control and the "green" policy that implements carbon emission control (of either carbon taxation or cap-and-trade). The final product is produced by the manufacturer using both new components and recycled used components. As such, the purpose of our paper is to study a similar problem from a single-stage perspective, by proposing a preliminary model of an integrated production-repair inventory system that considers three types of items simultaneously–service items, raw materials, and used items. The service items are produced from both the raw materials and the used items. The inventory control policies of these items are controlled by the same actor instead of three different actors. The demand is serviced by periodic deliveries and the costs of transportation and carbon emissions are considered. Unlike [5], the production run and repair run alternates with one another instead of running simultaneously as these processes share the same facility. A unique decision mechanism available to the inventory manager is that he or she can delay the repair run and the production run to reduce redundant inventory from accumulating (without incurring shortages), which ultimately leads to the unit time total cost function behaving in an unconventional way.

Numerous contributions to the literature of inventory models can be found; but if we consider the contributions that are related to this study, then we may divide these contributions into two groups, namely, the studies of production-recovery inventory models with continuous delivery or with periodic delivery (or JIT) delivery. Furthermore, among these two groups, the corresponding studies may be subdivided into studies that consider carbon emissions control and studies that do not.

Most of the earlier models in the literature are production-recovery models with continuous delivery and without carbon emissions control. As far as we know, it began with the work of Schrady [6], where he considered infinite production rate and repair rate, and policies of either multiple production runs with one repair run per cycle ((1,P) policy), or multiple repair runs with one production run per cycle ((R,1) policy). Later, [7] extended [6] to the case of finite repair rate and [8] extended to the multi-item case. After that, [9] considered (1,P) and (R,1) policies for the cases where the finite repair rate is either greater than the demand rate or less than or equal to the demand rate, and they gave EOQ formulas and found the optimal integer setup numbers numerically. [10] followed up by giving closed-form expressions for the optimal integer setup numbers, and [11–13] followed up by assuming finite production rate. [14–18] proposed waste disposal models by relaxing the assumption that all returned items are recoverable–these models assumed that a portion of the returned items are disposed at a cost. Finally, [19] generalized the waste disposal model to the case of finite production rate and finite repair rate under a (1, 1) policy, and then, [20] followed up by generalizing to the case of (P,R) policy. Note that all these production-recovery models consider two types of inventories simultaneously–used items and service items–in a single stage.

The above production-recovery models assumed continuous delivery. Some authors have studied models operating under periodic (or JIT) delivery, motivated by the idea that the frequent delivery of small lots of items can be economically desirable. [21] proposed a model that considers service items and raw materials inventories simultaneously, where the service items are delivered periodically. [22] compared the classical EPQ model with a revised EPQ model that incorporates JIT delivery, and focused their attention on modelling the costs so that the space savings of JIT situations are better1, Pflected, thus showing that JIT implementation is superior. [23] proposed a manufacturer-retailer two-stage model where the manufacturer conducts JIT deliveries to the retailer who operates with shortages that are backlogged. However, all these periodic delivery models do not consider used items recovery, unlike [5] that does.

In recent years, in the face of increasing environmental, legislative, and economic pressures, the academia has begun to account for the costs of carbon emissions in the mathematical modelling of production-recovery inventory systems. [24] developed a model operating under a (P,R) policy that includes the costs of GHGs emissions and energy usage from production, recovery, and transportation. [25] developed a two-stage supply chain model with no recovery in which the production process is imperfect and the items that are held in stock are subject to deterioration, and in which the vendor ships items to the buyer periodically. The authors considered carbon emission costs from transportation and warehousing in addition to the traditional costs. [26] developed a model where the production of new items and the remanufacturing of returned items create defective items that are perfectly repaired, and the authors considered the emissions of carbon in every stage of the system, which are taxed accordingly.

2 Mathematical Formulation

This section describes the problem and gives the assumptions and notations that are used in the mathematical formulation. We consider an inventory model that holds three types of items: used items, service items, and raw materials. The inventory policy is cyclic: each cycle starts with a repair run where all returned items are repaired to an as good as new condition, followed by a production run that converts the raw materials to service items. The shipping of the service items to the clients is periodic, where the shipments are of equal sizes and are delivered in equally spaced time intervals. We take the costs of carbon emission into account when determining which inventory policy to follow. The following assumptions are made to develop the mathematical formulation of the proposed model:

(1) A single-item inventory system is considered over an infinite planning horizon.
(2) The items are to service a known demand rate of D units per unit time.
(3) The demand is serviced periodically in equal-sized shipments. The periods between shipments are of equal length.
(4) The demand is supplied by production at a rate of P units per unit time (where $P > D$) and by repair of the used items at a rate of R units per unit time (where $R > D$).
(5) The used items are collected at a rate of θD units per unit time (where $0 < \theta < 1$). All used items are repaired to an as good as new condition.

(6) The production process converts a basket of raw materials into the service items. The raw materials are procured at a rate of M baskets per unit time (where $M > P$).
(7) Shortages are not allowed.
(8) Shipping and warehousing of items cause carbon emission.
(9) The distance d travelled for the shipping of items per trip is known and constant.
(10) The following cost structure is considered:

  (a) K_P, setup cost of production
  (b) K_R, setup cost of repair
  (c) K_M, setup cost of raw materials procurement
  (d) h_P, unit holding cost of service item per unit time
  (e) h_R, unit holding cost of used item per unit time
  (f) h_M, unit holding cost of basket of raw materials per unit time
  (g) h_e, average carbon emission cost from warehousing per unit stored per unit time
  (h) T_f, fixed shipping cost per trip
  (i) T_v, variable shipping cost per unit shipped per distance travelled
  (j) T_r, variable cost per distance travelled for the return trip
  (k) T_e, average carbon emission cost per distance travelled

The following notations are used to develop the mathematical formulation of the proposed model:

(1) N, the number of shipments per cycle
(2) S, the size of each shipment
(3) L, the time interval between shipments
(4) Q_R, the amount of used items that are repaired
(5) Q_P, the amount of items that are produced from raw materials
(6) T_0, the time at which a cycle starts (we set $T_0 = 0$ without loss of generality)
(7) $T_1^{'}$, the time at which the repair run in a cycle starts ($T_1^{'} \geq T_0$)
(8) T_1, the time at which the repair run in a cycle stops
(9) T_2, the time at which the raw materials procurement in a cycle stops
(10) T_3, the time at which the production run in a cycle starts
(11) T_4, the time at which the production run in a cycle stops
(12) T_5, the time at which a cycle end

An example of the movements of the three types of inventories in the proposed model is shown in Fig. 1 for the case of 6 shipments. In each cycle, the repair run will run its course first followed by the production run.

The points {1, 2, …, 6} in the graph of the service items in Fig. 1 represent the shipping points. The dashed blue line segments represent the pure build-up of inventory due to the repair run of rate R followed by the production run of rate P. For the sake of comparison, the solid grey line segments represent the inventory movement if delivery is continuous instead of periodic. From the blue dashed line segments, notice that the inventory level of the service items is either at or above the shipping points, thus ensuring

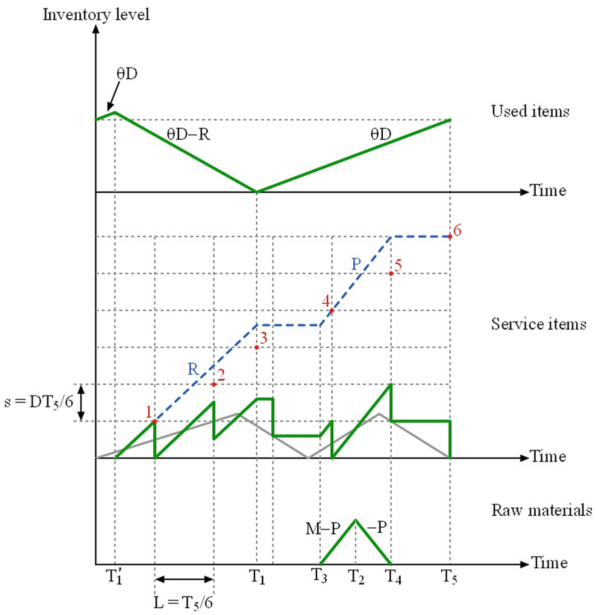

Fig. 1. The inventory movements in the proposed inventory system for Case 1 and for $N = 6$.

that shortage does not occur. This is always the case since R, P > D, as long as the repair run and the production run are not started too late. The green line segments represent the actual movement of inventory due to repair, production, and periodic shipping.

Supposing that there are N shipments in a cycle, we have $L = T_5/N$ and $S = (DT_5)/N$. Thus, the shipment times are given by

$$t_k = (kT_5)/N, \qquad k = 1, 2, \ldots, N. \tag{1}$$

Since $R > D$, the repair run can be delayed to starting at time $T_1^{'}$ before the first shipment at time T_5/N (instead of starting at time T_0) so that the accumulated inventory at the point of the first shipment is just enough for that shipment. The rationale for this delay is to reduce the unnecessary build-up of inventory from starting the repair run earlier than necessary. However, there are two cases to consider: (Case 1) there are enough used items to be repaired to meet the demand of the first shipment, and (Case 2) there are not enough used items.

Case 1: Since there are enough used items to be repaired to meet the demand of the first shipment, we have

$$T_1^{'} = \frac{R - D}{NR} T_5. \tag{2}$$

Since the amount of used items to be repaired is $Q_R = \theta DT_5$, we have

$$R\left(T_1 - T_1^{'}\right) = \theta DT_5, \tag{3}$$

which, from (2), gives

$$T_1 = \frac{R + N\theta D - D}{NR} T_5. \tag{4}$$

The number of shipments that the repair run fully provides for is $N_R = \lfloor Q_R/S \rfloor = \lfloor \theta N \rfloor$. Thus, the $(N_R + 1)$ th shipment needs to be at least partially provided for by the production run. Hence, the production run must start at time T_3 between time $N_R T_5/N$ and time $(N_R + 1)T_5/N$ so that the accumulated inventory at the point of the $(N_R + 1)$ th shipment is just enough for it. Thus, we have

$$T_3 = \frac{(P - D)(1 + \lfloor \theta N \rfloor) + N\theta D}{NP} T_5. \tag{5}$$

The amount of service items to be produced is $Q_P = (1 - \theta)DT_5$. We have

$$P(T_4 - T_3) = (1 - \theta)DT_5, \tag{6}$$

which, from (5), gives

$$T_4 = \frac{(P - D)(1 + \lfloor \theta N \rfloor) + ND}{NP} T_5. \tag{7}$$

Since the procurement rate M of raw materials is greater than the production rate P, then the procurement of raw materials must begin latest at time T_3 and must be concluded at time T_2 before time T_4. Thus, we have

$$M(T_2 - T_3) = P(T_4 - T_3), \tag{8}$$

which, from (5) and (6), gives

$$T_2 = \left[\frac{(P - D)(1 + \lfloor \theta N \rfloor)}{NP} + \frac{\theta D}{P} + \frac{D(1 - \theta)}{M} \right] T_5. \tag{9}$$

Case 2: Since there aren't enough used items to be repaired to meet the demand of the first shipment, then we need to start the production run before the first shipment to supplement the excess demand. To reduce the unnecessary build-up of inventory, the production run should start immediately after the repair run at time T_1 and produce just enough so that the accumulated inventory at the point of the first shipment is just enough for that shipment. Thus, we have

$$T_1 = \frac{P - D + N\theta D}{NP} T_5. \tag{10}$$

Since (3) holds for this case as well, we have

$$T_1' = \left(\frac{P - D + N\theta D}{NP} - \frac{\theta D}{R} \right) T_5. \tag{11}$$

This means the repair run can be delayed until time T_1'. And since the production run should start immediately after the repair run, we have $T_3 = T_1$.

Since (6) and (8) hold for this case as well, we have

$$T_4 = \frac{P + (N-1)D}{NP} T_5. \tag{12}$$

$$T_2 = \left[\frac{P - D + N\theta D}{NP} + \frac{D(1-\theta)}{M}\right] T_5. \tag{13}$$

Now, we have written the times $T_1^{'}$, T_1, T_2, T_3, and T_4 in terms of the cycle length T_5, where.

$$T_1^{'} < T_1 \leq T_3 < T_2 < T_4 < T_5. \tag{14}$$

For Case 1, notice that if $R = D$, then $T_1^{'} = 0$ and $T_1 = \theta T_5$. Moreover, notice that if $R = P = D$, then $T_3 = T_1$ and $T_4 = T_5$. For Case 2, T_3 is always equal to T_1. But, if $R = P = D$ and $N = 1$, then $T_1^{'} = 0$ and $T_4 = T_5$.

Finally, we give the condition that determines which case to employ as follows:

If $\theta \geq 1/N$, then employ Case 1, else employ Case 2.

Notice that Case 1 needs $N > 1$. Hence, for the case of one shipment at the end of the cycle ($N = 1$), Case 2 is always employed.

Next, consider the used items inventory. The area A_1 under the graph of the inventory level is given by the area of a triangle. This is because we may shift the part of the graph during the period $[0, T_1]$ to time T_5 since the inventory level at time 0 and at time T_5 are equal. Thus, we have

$$A_1 = \frac{\theta D}{2}\left(1 - \frac{\theta D}{R}\right) T_5^2. \tag{15}$$

Then, consider the service items inventory for Case 1. The area under the graph of the pure inventory build-up (the blue dashed lines in Fig. 1) represents the holding of inventory after the repair run and the production run without shipping anything out. Once the first shipment is completed at time T_5/N, the correspond-ing amount of stock is no longer held for the remaining period of length $T_5 - T_5/N$. That is, the area $S(T_5 - T_5/N)$ should be subtracted from the area under the graph of the pure inventory build-up. In general, once the kth shipment ($k = 1, 2, \ldots, N$) is completed at time kT_5/N, the corresponding amount of stock is no longer held for the remaining period of length $(N-k)T_5/N$. That is, the area $S(N-k)T_5/N$ should be subtracted from the remaining area. However, notice that the last shipment is completed at time T_5 (at the end of the cycle); hence for this shipment, there is no corresponding area to subtract. Thus, the actual area A_2 under the graph of the service items inventory level is given by

$$\begin{aligned} A_2 = {} & \text{Area under the blue dashed lines} \\ & - \sum_{k=1}^{N-1} \frac{S(N-k)T_5}{N}. \end{aligned}$$

After some algebraic manipulation, we get

$$A_2 = \left[\frac{2\theta D(NR - R + D) - N\theta^2 D^2}{2NR} - \frac{D(N-1)}{2N}\right.$$

$$+\frac{2(1-\theta)D(P-D)(N-1-\lfloor\theta N\rfloor)}{2NP}$$
$$+\left.\frac{N(1-\theta)^2D^2}{2NP}\right]T_5^2. \tag{16}$$

Next, consider the service items inventory for Case 2. The area under the graph of the pure inventory build-up is the sum of the areas of two trapezoids. Thus, the actual area A_2 under the graph of the service items inventory level is

$$A_2=\left[\frac{PD(N-1)-D^2(\theta N-1)}{NP}+\frac{\theta^2D^2}{2R}\right.$$
$$\left.-\frac{(1-\theta)^2D^2}{2P}-\frac{D(N-1)}{2N}\right]T_5^2. \tag{17}$$

Then, consider the case of the raw materials inventory. The area A_3 under the graph of the inventory level is also given by the area of a triangle. Thus, we have

$$A_3=\frac{(M-P)(1-\theta)^2D^2}{2MP}T_5^2. \tag{18}$$

The total cost per cycle is given by the sum of the setup costs, holding costs, emission costs, and transport costs. The total holding costs, considering both traditional holding costs and carbon emission costs due to warehousing (assuming that all items consume the same warehousing resources), is given by

$$C_H=(h_R+h_e)A_1+(h_P+h_e)A_2+(h_M+h_e)A_3. \tag{19}$$

We assume that the transport cost of moving items within the production and repair facilities are negligible. We also ignore the transport cost of procuring used items and raw materials since these procurements typically involve third parties whose transport policies are not within our control. Hence, the total transport costs, considering only the shipping of service items, is given by

$$C_T=N\left(T_f+T_rd+2T_ed\right)+T_vdDT_5. \tag{20}$$

Finally, the total cost per unit time ($TCUT$) in terms of the variables N and T_5 is given by

$$TCUT(N,T_5)=\frac{1}{T_5}(K_P+K_R+K_M+C_H+C_T). \tag{21}$$

The objective of the proposed model is to determine the optimal number of shipments (N^*) as well as the optimal cycle time (T_5^*) that minimizes $TCUT$.

3 Solution Procedure

First, we derive the square root formulas to find the optimal T_5^* for a fixed N. The fact that these formulas can be derived follows from the form of the $TCUT$, i.e.

$$TCUT(T_5)=\frac{A}{T_5}+BT_5+C,$$

where A, B, and C are constants. This is the convex form from the EOQ model. The following square root formula is clearly seen:

$$T_5^* = \sqrt{AB^{-1}}.$$

To find the optimal N^*, we start with $N = 1$ and find the corresponding T_5^*. Then we increment N by 1 and find the corresponding T_5^* again. Our numerical experiments have shown us that as N increases, the value of $TCUT^*$ increases and decreases, thus resulting in multiple local minima. But as N increases, the local minima follow an upward trend. Hence, we propose to find the optimal N^* by searching through a large number of N's and stopping when the $TCUT^*$ corresponding to the last N is many times larger than the best $TCUT^*$ that has been found so far.

4 Numerical Example and Sensitivity Analysis

Most of the parameter values that are used in the numerical example are adopted from [26] (e.g., the carbon emission and transportation costs). However, since the proposed model incorporates repair of used items and raw materials procurement, where the associated parameters have no counterpart in [26], random values that satisfy the assumptions that we made are adopted. The values are:

- $P = 2000000$ units/year,
- $D = 500000$ units/year,
- $R = 1000000$ units/year,
- $M = 2500000$ units/year,
- $K_P = \$100000$/setup,
- $K_R = \$80000$/setup,
- $K_M = \$2000$/setup,
- $h_P = \$60$/unit/year,
- $h_R = \$40$/unit/year,
- $h_M = \$20$/unit/year,
- $h_e = \$6.18$/unit/year,
- $T_f = \$500$/trip,
- $T_r = \$20$/km,
- $T_v = \$0.01$/unit/km,
- $T_e = \$0.048$/km,
- $d = 100$ km.

We illustrate both Case 1 and Case 2 by using two values for the parameter θ. When we set $\theta = 0.6$, we obtain the optimal value of N as $N^* = 2$, the minimum unit time total cost as $TCUT^* = \$3,123,837.05$, and the optimal cycle time as $T_5^* = 0.1426$ year. These values are obtained from implementing Case 1, since $\theta = 0.6 > 1/2 = 1/N$. In Fig. 2, the plot of $TCUT^*$ against N from $N = 1$ to $N = 100$ shows the upward trend of $TCUT^*$ with respect to N. When we set $\theta = 0.1$, we obtain $N^* = 1$, $TCUT^* = \$2,521,962.96$, and $T_5^* = 0.1825$ year. These values are obtained from implementing Case 2, since $N = 1$.

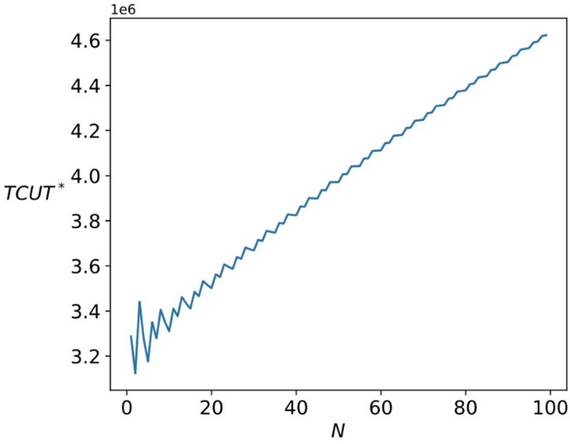

Fig. 2. Plot of $TCUT^*$ against N for the case of $\theta = 0.6$.

In the numerical sensitivity analysis, the set of parameters

$$X = \{D, \theta, (K_P, K_R, K_M), (h_P, h_R, h_M), d, h_e, T_e\}$$

is tested. The initial value of X is

$$X = \{500000, 0.6, (100000, 80000, 2000), (600, 40, 20), 100, 6.18, 0.048\}.$$

Except for θ, the parameter values are made to vary in the range from 50% to 140% of their initial values.

For testing the return rate θ, the unit time cost of production (CP) and the unit time cost of repair (CR) are included into the unit time total cost ($TCUT$) in order to reflect the economic advantage of used items recovery. This is because carrying used items incurs additional holding cost that will inflate the $TCUT$, but this can be counteracted by considering the typically cheaper cost of repair (compared to the cost of production). Hence, the following costs are added to the $TCUT$ expression:

$$C_P = \frac{Q_P w_p}{T_5}, \qquad C_R = \frac{Q_R w_R}{T_5},$$

where w_P is the unit production cost and w_R is the unit repair cost, and $w_P > w_R$. In this test, we set $w_P = \$10$ and $w_R = 0.6 w_P$. The values of θ are made to vary in the range [0.1, 0.8].

From the results of the sensitivity analysis, the following observations can be made:

(1) The optimal N^* is sensitive to the parameters D and θ and is insensitive to the other parameters.
(2) The optimal $TCUT^*$ is highly sensitive to the parameter D.
(3) $TCUT^*$ is more sensitive to the classical costs (K_P, K_R, K_M, h_P, h_R, h_M) than to the emission costs (he and Te). It is almost insensitive to Te.

(4) $TCUT^*$ is less sensitive to the parameter θ than to the parameters (D, K_P, K_R, K_M, h_P, h_R, h_M, d). When the unit time production cost and unit time repair cost are factored in, $TCUT^*$ decreases as the value of θ increases, but N^* increases as the value of θ increases.
(5) Both $TCUT^*$ and N^* increase as the value of the parameter D increases.
(6) $TCUT^*$ increases as the values of the parameters (K_P, K_R, K_M, h_P, h_R, h_M, d, h_e, T_e) increase over the prescribed range, but N^* remains stable.

5 Conclusion

This paper proposes an integrated inventory model that considers three types of inventories: used items, service items, and raw materials. Used items are collected from the market and are repaired as good as new to satisfy demand. If there are insufficient repaired items, then the remaining demand is satisfied by producing the required items from the stocked raw materials. Hence the policy that is adopted is cyclic, with one repair run and one production run per cycle. Demand is satisfied by shipping in equally spaced time intervals in batches of equal size. The warehousing of items incurs a carbon emission cost in addition to the traditional holding costs. Additionally, the transportation of items to the client also incurs a carbon emission cost in addition to the traditional transportation costs.

The numerical results showed that when repairing used items is cheaper than producing new items, then the additional costs that are incurred by carrying the used items and setting up the repair run are counteracted, and the optimal policy favours repair rather than production. We note that the emission costs that arise from repair and production can be included inside the unit production cost and unit repair cost, and thus, there is no loss of mathematical generality.

The numerical results further showed that the emission costs from warehousing and from the transportation of items to the client barely affects the optimal policy. Specifically, the optimal delivery frequency (N^*) is observed to be unaffected by the emission costs while the length of the cycle time (T_5) barely changes. The optimal policy is much more affected by the demand rate and the return rate. Perhaps a more realistic assessment of N^* vis-a-vis the emission costs can be made if the number of transportation vehicles and the max load of each vehicle are considered. This can be done in a future work. Another important item for future research is an analytical treatment of the behaviour of the value of $TCUT^*$ with respect to N; that is, what are the conditions that ensure the existence of a global minimum.

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