Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 17 May 2026
Revised 04 July 2026
Accepted 17 July 2026

Natural Resources for Human Health 2026, Vol. 6 (12s): 201–212

KEYWORDS:
Green Technology, Sustainable inventory, Imperfect quality items, Time-dependent demand, Environmental Cost.

Integrating EOQ Model and Green Technology for Sustainable Inventory System with Environmental Cost Considering Imperfect Quality Items and Time Dependent Demand

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ABSTRACT: The Economic Order Quantity (EOQ) model for a sustainable inventory system with imperfect-quality items is developed with the primary objectives of reducing carbon emissions and conserving the natural resources. The traditional inventory model that already exists has less consideration for the sustainable environment. Sustainable inventory model includes the green technology to minimize carbon emission and maximize the profit. The required costs are derived and to evaluate the mathematical model, an example is solved. The values of cycle time, optimum order quantity and the total profit are determined. The incorporation of green costs into the inventory model is intended to mitigate environmental impacts while enhancing overall profitability. The objective function of the mathematical model is to find the total profit that includes environmental cost or green cost. The total profit it difference between sales revenue and total costs. Furthermore, green investment plays a crucial role in conserving natural resources, promoting environmental sustainability, and ensuring the availability of these resources for future generations.

INTRODUCTION

The Classical Economic Order Quantity (EOQ) model is one of the fundamental concepts in inventory management and operations research. It is widely used to determine the optimal order quantity that minimizes the total inventory cost by balancing two major cost components: ordering cost and holding cost. Ordering cost includes the fixed expenses incurred whenever an order is placed, such as administrative expenses, transportation charges, and delivery costs. Holding cost refers to the expenses associated with storing inventory, including warehousing, insurance, depreciation, and the opportunity cost of capital. The classical EOQ model is developed under several assumptions, such as constant demand, instantaneous replenishment, no shortages, and perfect-quality items. In recent years, environmental sustainability has become an important consideration in inventory management. A sustainable environment refers to a state of environmental equilibrium in which natural resources, including air, water, soil, climate, and ecosystems, are conserved and maintained to satisfy the needs of the present generation without compromising the ability of future generations to meet their own needs. Sustainable development therefore emphasizes the conservation of natural resources, reduction of pollution, protection of biodiversity, and the efficient utilization of environmental resources.

In practical manufacturing systems, however, the assumption that all finished products are of perfect quality is often unrealistic. During each production cycle, a certain proportion of items may be of imperfect quality due to production-related uncertainties.

These defective items are subsequently inspected and repaired, resulting in additional repair costs that increase the overall inventory cost. Therefore, incorporating imperfect-quality items into the EOQ framework provides a more realistic representation of industrial inventory systems. To promote environmentally sustainable inventory management, the concept of green technology is incorporated through the inclusion of green costs (environmental costs). These costs represent the environmental impacts associated with inventory operations and include carbon emission costs during production, transportation emission costs, waste disposal costs, emissions generated during the repair of defective items, pollution control costs, and investments in green technologies. Consequently, the total inventory cost consists of production cost, repair cost associated with imperfect-quality items, and green (environmental) costs. By integrating environmental costs with the traditional EOQ framework, the proposed model provides a comprehensive approach to achieving economic efficiency while reducing environmental impacts and promoting sustainable inventory management.

LITERATURE REVIEW

In face of escalating environmental challenges such as climate change, resource depletion, pollution and biodiversity loss. Environmental sustainability refers to the responsible interaction with the environment to avoid depletion of natural resources and ensuring long term ecological balance. The method of achieving environmental sustainability is the adoption and advancement of Green Technology. Many researchers are developed the mathematical model related to the green concepts. A sustainable manufacturing–remanufacturing inventory model is created with price and green sensitive demand for defective and usable items. [1]. A green inventory model is developed for considering environmental emissions under carbon tax, cap-and-offset, and cap-and-trade regulations [2]. An EOQ model for deteriorating products with green technology investment and trade credit financing [3]. EOQ models for imperfect items developed with under time varying demand rate [4]. Inventory optimization in a green environment with two warehouses [5]. A green inventory model with the effect of carbon taxation [6]. A production inventory model for green products with emission reduction technology investment and green subsidy [7]. A green inventory model with imperfect items considering inspection process and quality improvement under different shortages scenarios [8]. Green inventory model with two-warehouse system considering variable holding cost, time dependent demand, carbon emissions and energy consumption [9]. Optimization of an inventory model for deteriorating items with both selling price and time-sensitive demand and carbon emission under green technology investment [10].

METHEDOLOGY

Notations

To develop the proposed model, the following notations and assumptions are used.

$B(t)$	Inventory level
x	Optimum order quantity
D	Demand rate
X	Inspection rate
R	Repair rate
λ	Fraction of defective items
M	Markup percentage by the repair shop (%)
T	Cycle time
t_I	Time to screen a lot size x
t_R	Time to transport, repair and return imperfect items to the buyer (years)
t_T	Total transport time

S	Transportation fixed cost
L	Repair setup cost
K	Buyer's order cost
Y	Unit price
c_i	Unit inspection cost
c_u	Unit cost
c_s	Unit salvage cost
c_t	Unit transportation cost
c_r	Unit repair cost charged to the buyer
c_2	Material and labor cost to repair an item
c_e	Unit purchasing cost of an emergency order
h_g	Holding cost of a good quality item
h'	Holding cost at the repair facility
h_r	Holding cost of a repaired item
h_e	Holding cost of an emergency-ordered item
σ	Unit of carbon emission per replenishment
g	Unit variable emissions in the warehouse
b	Social cost from vehicle emission
d_t	Distance travelled from supplier to buyer
a_u	Average velocity
F_d	Fixed cost of disposing waste to the environment
W_d	Cost of disposing waste to the environment
θ	Proportion of waste produced per lot $(0 \le \theta \le 1)$
α	Proportion of waste returned
e	Carbon emission price/carbon tax
m_e	Carbon emission from manufacturing
r_e	Carbon emission from recycling process

C_f	The fixed capital cost of pollution control for production run
C_o	The operating and maintenance cost of pollution control per unit of production quantity
π	The Pollution factor
G	Capital amount invested on green technology

ASSUMPTIONS

- The repair process of the items at the third-party shop is always in control.
- The percentage of defective items λ is fixed.
- The inspection rate X and the repair rate R are constant.
- The inspection rate always exceeds the demand rate, that is X > D.
- The parameters of the demand function are m>0 and n >0.
- Shortage of inventory is not permitted.
- All the stock will be sold out at the end of the cycle (0 < T < 1).
- The Proportion of the demand and returned products are constant per cycle.
- The replenishment is instantaneous.
- The company has the opportunity to invest on Green technology in each source of emissions separately to reduce emissions.
- Waste management focuses on source reduction, pollution prevention and disposal.

MATHEMATICAL MODEL

The first option treats imperfect items by sending them to be repaired at a third party facility. After restoration, the items are returned to the inventory. At the beginning of each batch, a lot of x is received and depleted at the rate of D. The derivation begins by assuming a linear function for the demand rate. Repairing the defective items

$$\frac{dv}{dt} = -D$$

$$\frac{dv}{dt} = -m - nt, \qquad m, n > 0 \tag{1}$$

The inventory function, $B(t)$ is obtained by integration:

$$\int_{x}^{B(t)} du = \int_{0}^{t} (-m - nt)\ dt$$

$$B(t) = x - mt - \frac{nt^2}{2} \tag{2}$$

The boundary condition, $B(t) = 0$ gives

$$x = mT + \frac{nT^2}{2} \tag{3}$$

and from $\displaystyle\int_{B(t_1)-\lambda y}^{0} du = \int_{t_I}^{t_P} (-m - nt)\ dt$

We obtain $B(t_I)=\lambda y+mt_p+\frac{nt_p}{2}-mt_I-\frac{nt_I^2}{2}$ (4)

Substituting t_I into (2) we obtain $B(t_I)=x-mt-\frac{nt_I^2}{2}$ and substituting (3) into (4) gives,

$$x-mt_I-\frac{nt_I^2}{2}=\lambda\left(mT+\frac{nT^2}{2}\right)+mt_p+\frac{nt_p^2}{2}-mt_I-\frac{nt_I^2}{2}$$

Thus, $t_p^2=\frac{-2mt_p+(1-\lambda)(2mT+nT^2)}{n}$ (5)

Multiply equation (5) with t_p and replace the term t_p^2 on the right side with (5) gives

$$t_p^3=\frac{\left[n(1-\rho)(2mT+nT^2)+4m^2\right]-2m(1-\lambda)(2mT+nT^2)}{n^2} \quad (6)$$

Equations (5) and (6) are used when the terms t_p^2 and t_p^3 occurs. It can be replaced with in terms of t_p only.

The area during the repair interval

$$S_1+S_2+S_3=\int_0^{t_I}B(t)\,dt+\int_{t_I}^{t_p}\left(B(t)-\lambda x\right)dt$$

$$=\int_0^{t_I}x-mt-\frac{nt^2}{2}\,dt+\int_{t_I}^{t_p}(1-\lambda)x-mt-\frac{nt^2}{2}\,dt$$

$$=\left[(1-\lambda)t_p+\lambda t_I\right]x-\frac{mt_p^2}{2}-\frac{nt_p^3}{6} \quad (7)$$

$$S_1+S_2+S_3=\frac{\left[2n(1-\lambda)(2mT+nT^2)+2m^2\right]t_p}{6n}-\frac{m(1-\lambda)(2mT+nT^2)}{6n}+\frac{\lambda(2mT+nT^2)^2}{4L} \quad (8)$$

The equation (8) is obtained from equations (3), (5), (6) and (i), (ii) are given below:

(i) $t_i=\frac{x}{X}=\frac{2mT+nT^2}{2X}$

(ii) $t_S=\frac{\rho x}{R}+t_T=\frac{\rho(2mT+nT^2)}{2R}+t_T$.

$$S_4=\int_{t_I+t_S}^{T}B(t)\,dt-\int_{t_I+t_S}^{t_P}\left(B(t)-\lambda x\right)dt$$

$$=\int_{t_P}^{T}\left(x-mt-\frac{nt^2}{2}\right)dt-\int_{t_I+t_S}^{t_P}\lambda x\,dt$$

$$= x(T-t_P)-\frac{aT^2}{2}-\frac{bT^3}{6}+\frac{at_P^2}{2}+\frac{bt_p^3}{6}+\lambda x(t_P+t_I+t_S)$$

$$= -\left[((1-\lambda)t_P+\lambda t_I)x-\frac{at_P^2}{2}-\frac{bt_p^3}{6}\right]-\lambda x t_S+xT-\frac{aT^2}{2}-\frac{bT^3}{6}$$

$$= -(S_1+S_2+S_3)-\frac{\lambda t_T(2aT+bT^2)}{2}-\frac{\lambda^2(2aT+bT^2)^2}{4R}+\frac{aT^2}{2}+\frac{bT^3}{6} \tag{9}$$

The area during the repair interval is derived. Then the following costs are calculated with the given values.

1. The number of units need to be sent for repair is λx.
2. The total payment for repair is $c_2\lambda x$.
3. The amount that needs to be paid for transportation is $2c_t\lambda x$. (The transportation cost is multiply by 2 because of the two-way transport. one is cost of delivering the imperfect items to the repair facility and the cost for resending the repaired items)
4. The holding cost at the repair facility is denoted by $h' t_S \lambda x$.
5. The fixed amount of repair setup cost and transportation cost needs to be paid.
6. The markup percentage (%) by the repair shop is included in the calculation of the total cost of each repaired item $c_r(x)$.

The total cost of each repaired item is,

$$c_r(x)=(1+M)\left(\frac{L+2S}{\lambda x}+c_2+2c_t+h' t_S\right)$$

The holding cost per cycle $H(x)$,

$$H(x)=h(S_1+S_2+S_3)+h_r S_4.$$

The total cost per unit $TC(x)$ is,

$$TC(x)=K+(c_u+c_I)x+c_r(x)+H(x)$$

$$\left.\begin{array}{r}\text{The objective function of the mathematical model}\\ \text{is total profit unit time } TP(x)\end{array}\right\}=\frac{\left[\begin{array}{l}\text{The total revenue per cycle }-\\ \text{The total cost per cycle}\end{array}\right]}{\text{Cycle time}}$$

$$TP(x)=\frac{Yx-TC(x)}{T}$$

After the value of T^* which maximizes $TP(x)$ is obtained, the optimal order size x^* can be calculated. x can be expressed as a function of T.

$$\frac{TC(x)}{T}=\frac{1}{T}\left[K+(c_u+c_I)x+c_r(x)\lambda x+H(T)\right]$$

$$= \left\{ \begin{array}{l} \frac{K}{T} + (c_u + c_I)\left[\frac{2m+nT}{2}\right] + (1+M)\left\{\left[\frac{L+2S}{T}\right] + (c_2 + 2c_T)\lambda\left[\frac{2m+nT}{2}\right]\right\} \\ + h^{'}(1+M)\left[\frac{\lambda^2(2mT+nT^2)(2m+nT)}{4R} + t_T\left(\frac{2m+nT}{2}\right)\right] \end{array} \right\} \quad (10)$$

By equations (8) and (9),

$$\frac{H(T)}{T} = \frac{1}{T}\left[(h_g - h_r)(S_1 + S_2 + S_3) + h_r\left(\frac{mT^2}{2} + \frac{nT^3}{3} - \frac{\lambda t_T(2mT+nT^2)}{2} + \frac{\lambda^2(2mT+nT^2)^2}{4R}\right)\right]$$

$$= \left\{ \begin{array}{l} (h_g - h_r)\left[\frac{2m(1-\lambda)(2mT+nT)t_P}{6n} + \frac{m^2 t_P}{3nT} - \frac{m(1-\lambda)(2m+nT)}{6b} + \frac{\lambda(2m+nT^2)(2m+nT)}{4X}\right] \\ + h_r\left[\frac{mT}{2} + \frac{nT^2}{3} - \frac{\lambda t_T(2m+nT)}{2} - \frac{\lambda^2(2mT+nT^2)(2m+nT)}{4R}\right] \end{array} \right\}$$

…..(11)

Using Equations (10) and (11), get the total cost

$$TP(x) = \frac{Yx - TC(x)}{T}$$

$$= \left\{ \begin{array}{l} \left[\frac{2m+nT}{2}\right]A_1 + \left[\frac{(2mT+nT^2)(2m+nT)}{4}\right]A_2 + \left[\frac{mT}{2} + \frac{nT^2}{3}\right]A_3 \\ + \frac{A_4}{T} + (2m+nT)t_P A_5 + \frac{t_P}{T}A_6 \end{array} \right\} \quad (12)$$

Where the constants A_1, A_2, A_3, A_4, A_5 and A_6 are defined as follows:

$$A_1 = Y - c_u - c_I - (1+M)(c_2 + 2c_t + h^{'}t_T)\lambda + h_r\lambda t_T + \frac{m(1-\lambda)(h_g - h_r)}{3n}$$

$$A_2 = \frac{h_r\lambda^2}{R} - \frac{\lambda(h_g - h_r)}{X} - \frac{h^{'}\lambda^2(1+M)}{R}$$

$$A_3 = -h_r$$

$$A_4 = -[K + (1+M)(L+2S)]$$

$$A_5 = -(h_g - h_r)\left[\frac{2n(1-\lambda)}{6n}\right]$$

$$A_6 = -(h_g - h_r)\left(\frac{m^2}{3n}\right)$$

Equation (5) is quadratic so the value of t_p,

$$t_P = \sqrt{\left(\frac{m}{n}\right)^2 + (1-\lambda)\left[2\left(\frac{m}{n}\right)T + T^2\right]} - \left(\frac{m}{n}\right)$$

The first and second derivatives of t_P with respect to T.

$$\frac{dt_P}{dT} = \frac{(1-\lambda)\left[\frac{m}{n} + T\right]}{\sqrt{\left(\frac{m}{n}\right)^2 + (1-\lambda)\left[2\left(\frac{m}{n}\right)T + T^2\right]}} \tag{13}$$

$$\frac{dt_P^2}{dT^2} = \frac{(1-\lambda)}{\sqrt{\left(\frac{m}{n}\right)^2 + (1-\lambda)\left[2\left(\frac{m}{n}\right)T + T^2\right]}} - \frac{(1-\lambda)^2\left[\frac{m}{n} + T\right]^2}{\left\{\left(\frac{m}{n}\right)^2 + (1-\lambda)\left[2\left(\frac{m}{n}\right)T + T^2\right]\right\}^{\frac{3}{2}}} \tag{14}$$

Calculating the derivatives of t_P allows $TP(x)$ to be differentiated with respect T:

$$\frac{dTP(T)}{dT} = \left\{\begin{array}{l} \left(\frac{n}{2}\right)A_1 + \left[\frac{(2m+3nT)(2m+nT)}{4}\right]A_2 + \left(\frac{m}{2} + \frac{2nT}{3}\right)A_3 - \frac{A_4}{T^2} \\ + \left[nt_P + (2m+nT)\frac{dt_P}{dT}\right]A_5 + \left(\frac{1}{T}\frac{dt_p}{dT} - \frac{t_p}{T^2}\right)A_6 \end{array}\right\} \tag{15}$$

The necessary condition for $TP(T)$ to be maximum is

$$\frac{dTP(T)}{dT} = 0 \tag{16}$$

The value of T^* is obtained from equation (16) and optimal order stock quantity is calculated by the following formula:

$$x^* = mT^* + \frac{n(T^*)^2}{2} \tag{17}$$

The second derivative of $TP(T)$ is computed.

$$\frac{d^2TP(T)}{dT^2} = \left\{\begin{array}{l} \left(\frac{8mn + 6n^2T}{4}\right)A_2 + \left(\frac{2n}{3}\right)A_3 + \frac{2}{T^3}A_4 + \left[2n\frac{dt_P}{dT} + (2m+nT)\frac{d^2t_P}{dT^2}\right]A_5 \\ + \left(-\frac{2}{T^2}\frac{dt_p}{dT} + \frac{1}{T}\frac{d^2t_P}{dT^2} + \frac{2t_P}{T^3}\right)A_6 \end{array}\right\} \tag{18}$$

The value of $\frac{d^2TP(T)}{dT^2}$ is obtained at $T = T^*$ must be negative. This result is indicate that $TP(T^*)$ is maximum.

The introduction of Green Technology by means of incorporating the Environmental Cost as Green Cost,

(i) Emission cost during production $C_1(x) = \left(\delta + \dfrac{gx^2}{2D}\right) C_e$

(ii) Emission cost from transportation $C_2(x) = \left(\dfrac{2bd_t}{a_i}\right)$

(iii) Waste disposal cost $C_3(x) = F_d + W_d\, x(\theta + \alpha)$

(iv) Emission during repairing the defective items $C_4(x) = e(m_e + r_e)$

(v) Pollution control cost $C_5(x) = C_f + C_0\, \pi x$

(vi) The amount of capital invested on green technology $C_6(x) = G$

The total cost for the entire production process which includes the cost of repairing the defective items with concern of environment are expressed as follows.

$$TP(x) = \left\{ \begin{array}{l} \left[\dfrac{2m + nT}{2}\right] A_1 + \left[\dfrac{(2mT + nT^2)(2m + nT)}{4}\right] A_2 + \left[\dfrac{mT}{2} + \dfrac{nT^2}{3}\right] A_3 \\ + \dfrac{A_4}{T} + (2m + nT)\, t_P\, A_5 + \dfrac{t_P}{T} A_6 \end{array} \right\} + \tag{19}$$
$$\left[\left(\delta + \frac{gx^2}{2D}\right) C_e + \left(\frac{2bd_t}{a_i}\right) + F_d + W_d\, x(\theta + \alpha) + e(m_e + r_e) + C_f + C_0\, \pi x + G\right]$$

Numerical Example

Consider the following parameters to illustrate the proposed model:

D	50,000 units/year
X	175,200 units/year
R	50,000 units/year
t_T	2 / 200 year
M	20%
λ	0.02
m	50,000
n	5
K	\$ 100
S	\$ 200
L	\$ 100
Y	\$ 50/unit

Natural Resources for Human Health
eISSN: 2583-1194

c_i	\$ 0.5/unit
c_u	\$ 25/unit
c_s	\$ 20/unit
c_t	\$ 2/unit
c_2	\$ 5/unit
c_e	\$ 40/unit
h_g	\$ 5/unit/year
h'	\$ 4/unit/year
h_r	\$ 6/unit/year
h_e	\$ 8/unit/year
σ	200 (kg of CO_2 /order)
g	3 (kg of CO_2 /order)
C_e	\$ 10
b	\$ 30
d_t	20 km
a_u	4 km/h
F_d	\$ 20
W_d	\$ 5
θ	0.1
α	0.1
e	0.2
m_e	\$ 300
r_e	\$ 200
C_f	40
C_c	4pr

π	0.3
G	$ 1135

Using the condition (16), solve equation (15) then will get a value of T^*. Then substitute the value of T^* in (17) result indicates the value of optimum order quantity (x^*). Again substitute all the given and found values in (19) that represents a final total cost of entire production process with Green Technology.

RESULTS AND DISCUSSION

The numerical example is solved for the proposed inventory model. The results are, total profit $ 1,306,453.02, the cycle time is 0.075 years, optimum order quantity is 3732 units and the first and second derivative value of the total profit is 1,195,456.24 and -365,714.47 respectively. These findings are consistent with earlier studies on sustainable inventory management, which emphasized the benefits of integrating environmental factors into EOQ models. Previous research has also demonstrated that manufacturing–remanufacturing inventory systems with time dependent demand provide an effective approach for managing both serviceable and defective items. Similarly, the inclusion of green costs and repair costs in the present model offers a more realistic representation of practical production systems. The proposed framework supports sustainable manufacturing by simultaneously improving profitability, reducing environmental impacts, and promoting efficient resource utilization. From the results total profit of the manufacturing process is increased while comparing the existing inventory model. Optimum order quantity and the cycle time variation is negligible. A sustainable manufacturing–remanufacturing inventory model is created with time dependent demand for defective and usable items. [1]. A green inventory model is developed for considering environmental emissions under carbon tax, cap-and-offset, and cap-and-trade regulations [2]. An EOQ model for deteriorating products with green technology investment and trade credit financing [3]. . EOQ models for imperfect items developed with under time varying demand rate [4]. Inventory optimization in a green environment with two warehouses [5]. A green inventory model with the effect of carbon taxation [6]. A production inventory model for green products with emission reduction technology investment and green subsidy [7]. A green inventory model with imperfect items considering inspection process and quality improvement under different shortages scenarios [8]. Green inventory model with two-warehouse system considering variable holding cost, time dependent demand, carbon emissions and energy consumption [9]. Optimization of an inventory model for deteriorating items time dependent demand and carbon emission under green technology investment [10].

CONCLUSION

The mathematical model for Economic Order Quantity (EOQ) with imperfect items and introducing the green technology is formulated and analyzed by an example. The results are total profit $ 1,306,453.02, the cycle time is 0.075 years, optimum order quantity is 3732 units and the first and second derivative value of the total profit is 1,195,456.24 and -365,714.47 respectively. The results demonstrate that the model enhances total profitability while supporting sustainable inventory management with minimal changes in the optimal inventory policy. Consequently, the proposed framework provides a practical decision-making tool for manufacturers seeking to balance profitability with environmental responsibility. The total profit of the manufacturing process is increased while comparing the existing inventory model. The repairing process may have the additional charges, introducing the environmental cost as green cost reducing the carbon emission and made the environment sustainable for future generations. Using green technology for industries increasing the amount of total cost and reducing the carbon emission. So the penalty paid by the industries to the government is reducing gradually and by it may be negligible. The total profit is increased because of incorporating the green technology into the inventory models. The Green Inventory model created for handling the defective item and goodness of the environment. Future research may extend the model by considering stochastic demand, shortages, carbon cap-and-trade policies, multi-item inventory systems, or fuzzy and game-theoretic approaches to address real-world uncertainties.

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