Sustainable Inventory Optimization: A Multi-Item EOQ Model with All-Unit Discount, Capacity Constraint, and Carbon Emission

Manuscript received May 24, 2026; revised July 16, 2026

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***Abstract*— Inventory is one of the operational components that contributes to carbon emissions through warehouse electricity consumption; however, this aspect has not yet been integrated into conventional inventory models, despite growing attention to green supply chain management. This study develops a multi-item Economic Order Quantity model that considers all-unit discounts, warehouse capacity constraints, and carbon emissions as cost components and examines the effect of carbon emission variables on the mathematical model structure. The development was carried out by adding a carbon cost variable, calculated as the product of average warehouse energy consumption, the carbon emission factor, and the carbon tax, to the storage cost equation and the formula for the optimal reorder interval. Solutions were obtained through an iterative approach to determine a valid discount price interval. Proportional adjustments were then applied to satisfy the warehouse capacity constraint. A numerical example involving three product items yielded an optimal cycle time t* = 0.144 periods, a reorder interval after capacity adjustment G = 0.108 periods, and total inventory costs of IDR 2,086,099,971 per planning period. The addition of carbon emission variables increases the holding cost component and reduces the optimal reorder interval compared to the reference model, resulting in a total inventory cost IDR 1,488,996 higher than the reference model. Sensitivity analysis results indicate that warehouse capacity has the greatest influence on total costs compared to carbon emission parameters. This study contributes to the integration of environmental aspects into a deterministic multi-item inventory model, thereby providing a more comprehensive decision-making framework for retail managers.**

Keywords*— *All-Unit Discount, Carbon Emission, Economic Order Quantity, Multi-Item Inventory, Sustainable Inventory, Warehouse Capacity Constraint.

I. INTRODUCTION

Effective inventory management is a key factor in the operational success of a supply chain, as it directly affects a company's storage and ordering costs and working capital [1], [2]. In deterministic inventory systems, the Economic Order Quantity (EOQ) model is the most widely used approach due to its clear calculation structure and ease of implementation [3], [4], [5]. In multi-item retail environments such as minimarkets, the EOQ model can be extended by incorporating warehouse capacity constraints and all-unit discount policies, which create a trade-off between discount utilization and storage space limitations [4], [5].

The EOQ model has undergone substantial development to accommodate the growing complexity of inventory systems. Originally formulated for single-item systems under simplified assumptions, the model has since been expanded to address multi-item settings by incorporating various pricing policies, including all-unit discounts and incremental discounts [6]. Subsequent extensions introduced warehouse capacity constraints to reflect the physical limitations encountered by retail companies in practical inventory management [4], [5].

As attention to green supply chain management continues to grow, inventory activities are no longer evaluated solely from an economic standpoint. Storing goods requires continuous energy for lighting, cooling, and warehouse maintenance, while all-unit discount policies that encourage bulk purchasing extend storage durations and further increase energy consumption [7], [8]. Studies on supermarket retail operations show that inventory activities such as upstream logistics, warehouse energy use, and procurement generate measurable greenhouse gas emissions across the value chain [9]-[11]. These operational patterns generate carbon emissions that are seldom explicitly considered in conventional inventory models, despite increasing regulatory pressure on companies to address the environmental impact of their operations [9], [12], [13]. In several countries, this pressure has materialized into concrete policy instruments such as carbon tax regulations, which directly impose financial consequences on emission-generating business activities including inventory operations [12], [14],[15].

The integration of carbon emissions into inventory models has become an increasingly active area of research. Several studies have demonstrated that environmental considerations significantly influence optimal ordering decisions, particularly through carbon tax mechanisms that can substantially alter inventory cost structures [12], [16], [17]. In retail settings specifically, carbon regulations have been shown to drive firms to revise their inventory strategies, particularly when order-volume discounting schemes are in place, because the interaction between discount utilization and emission costs directly affects optimal ordering policies [18]. These findings confirm that incorporating carbon emissions into inventory models is not only environmentally relevant but also produces measurable effects on ordering policies and total inventory costs.

Existing studies have addressed these elements only partially. Silitonga and Moses [18] developed a multi-item EOQ model incorporating all-unit discounts and warehouse

 EISSN: 2961-872X ●PISSN: 2961-8924●DOI: 10.56741/IISTR.esl.002319

capacity constraints but did not account for carbon emissions. Pramesti et al. [19] integrated carbon emission costs into an inventory model but limited the scope to a single-item setting without warehouse capacity constraints. No existing model simultaneously integrates all three elements within a unified analytical framework [20]-[23]. This study addresses that gap by developing a multi-item EOQ model that incorporates all-unit discounts, warehouse capacity constraints, and carbon emissions as explicit cost components, and by identifying the effect of carbon emission variables on the mathematical structure of the model.

II. METHOD

A. Model Description

The model developed in this study applies to multi-item retail inventory systems such as minimarkets, with deterministic demand that remains constant over a one-year planning horizon. All items are ordered from a single supplier under a joint ordering policy, where the supplier applies an all-unit discount based on predefined quantity intervals. The order quantity for each item is adjusted proportionally to warehouse capacity as a physical constraint of the system. Carbon emissions resulting from the warehouse's electricity consumption during the storage period are incorporated as an additional cost component into the reference model [14], enabling the developed model to simultaneously integrate economic and environmental aspects. Transportation emissions are not explicitly modeled because the joint ordering policy consolidates all item replenishments into a single delivery, thereby inherently minimizing distribution emissions.

B. Assumptions

The following assumptions are adopted in this model:

- Demand is deterministic and occurs continuously at a constant rate throughout the planning horizon.
- All items are ordered from a single supplier under a joint order policy, with instantaneous replenishment and known lead time.
- No stockout occurs and all items are in good condition with no expiration during storage.
- Warehouse capacity is constant and expressed in units compatible with all stored items.
- Average warehouse energy consumption and carbon tax rate are known and constant throughout the planning horizon.

C. Notation

The notation used in this model is as follows:

- D_i : Demand of item-i over the planning horizon (units/period)
- C_{ij} : Unit price of item-i at discount interval j (IDR/unit)
- S : Ordering cost per order (IDR/order)
- n : Number of items
- H_i : Holding cost of item-i per unit per period, considering discount and carbon emission: Hi = hij·Cij + $w_e \times E_e \times t_x$ (IDR/unit·period)
- H_ij : Holding cost percentage per period relative to the unit price of item-i at discount interval j
- Q_i^* : Economic order quantity for item-i (units)
- T^* : Optimal reorder interval (period)
- r : Number of discount price intervals
- N : Order frequency
- QwP_i^* : Volume proportion of item-i considering warehouse capacity
- Qw_i^* : Volume requirement of item-i (m^3)
- QW_i^* : Volume of item-i after considering warehouse capacity (m^3)
- Qg_i^* : Economic order quantity for item-i after considering warehouse capacity (units)
- W : Warehouse capacity (m^3)
- wi : Volume per unit of item-i (m^3/unit)
- G : Reorder interval after considering warehouse capacity (period)
- t_x : Carbon tax rate (IDR/ton CO_2)
- w_e : Average warehouse energy consumption (kWh/unit·period)
- E_e : Grid emission factor of Indonesia (ton CO_2/kWh-)
- C_p : Total purchasing cost per planning period (IDR/period)
- C_o : Total ordering cost per planning period (IDR/period)
- C_h : Total holding cost per planning period (IDR/period)
- TIC : Total inventory cost per planning period (IDR/period)

D. Model Formulation

The model consists of three cost components: purchasing cost (C_p), ordering cost (C_o), and holding cost (C_h), which together form the total inventory cost (TIC).

Purchasing Cost

The purchasing cost is calculated based on the unit price of each item at the applicable discount interval multiplied by the demand of each item over the planning horizon.

$$C_p = \sum_{i=1}^{n} C_{ij} \cdot D_i \quad (1)$$

Ordering Cost

The ordering cost arises from the multiplication of the order frequency (N) and the cost per order (S_n), which can be expressed as:

$$Co = N \times S_n$$

If the order period $t = \frac{1}{N}$ is identical for all items under the joint ordering policy, such that $t_1 = t_2 = t_3 = \ldots = t_n$, the ordering cost equation becomes:

$$C_o = \frac{S}{T^*} \quad (2)$$

 EISSN: 2961-872X ●PISSN: 2961-8924●DOI: 10.56741/IISTR.esl.002319

where t* denotes the optimal reorder interval obtained when the ordering periods of all items are synchronized.

Holding Cost

The holding cost extends the reference model by incorporating a carbon cost component $w_e \times E_e \times t_x$ into the per-unit holding cost.

$$C_h = \frac{1}{2}\sum_{i=1}^{n} t^* \cdot D_i \cdot \left(h_{ij} \cdot C_{ij} + w_e \cdot E_e \cdot t_x\right) \quad (3)$$

Total Inventory Cost

$$TIC = \sum_{i=1}^{n} C_{ij} \cdot D_i + \frac{S}{G} + \frac{1}{2}\sum_{i=1}^{n} G \cdot D_i \cdot \left(h_{ij} \cdot C_{ij} + w_e \cdot E_e \cdot t_x\right) \quad (4)$$

Optimal Reorder Interval

The optimal reorder interval is obtained by minimizing TIC with respect to T^*.

$$TIC = \sum_{i=1}^{n} C_{ij}.D_i + \frac{S}{T^*} + \frac{1}{2}\ \sum_{i=1}^{n} T^*.\ D_i.(h_i.C_{ij}\ + w_e.E_e.t_x)$$

$$\frac{\vartheta \sum_{i=1}^{n} C_{ij}.D_i + \frac{S}{T^*} + \frac{1}{2}\sum_{i=1}^{n} T^*.D_i.(h_i.C_{ij} + w_e.E_e.t_x)}{\vartheta T^*} = 0$$

$$0 - \frac{S}{T^{*2}} + \frac{1}{2}\ \sum_{i=1}^{n} D_i.(h_i.C_{ij}\ + w_e.E_e.t_x) = 0$$

$$\frac{1}{2}\ \sum_{i=1}^{n} D_i.(h_i.C_{ij}\ + w_e.E_e.t_x) - \frac{S}{T^{*2}} = 0$$

$$\frac{1}{2}\ \sum_{i=1}^{n} D_i.(h_i.C_{ij}\ + w_e.E_e.t_x) = \frac{S}{T^{*2}}$$

$$T^{*2} = \frac{2s}{\sum_{i=1}^{n} D_i.(h_i.C_{ij} + w_e.E_e.t_x)}$$

$$T^* = \sqrt{\frac{2s}{\sum_{i=1}^{n} D_i\ .(h_i\ .\ C_{ij} + w_e.E_e.t_x)}} \quad (5)$$

E. Solution Procedure

The solution procedure for determining the optimal inventory policy follows an iterative approach adapted from Silitonga and Moses [14], with modifications to the T^* and TIC formulas to incorporate the carbon emission cost component. The procedure is as follows:

1. Determine the values of the model input parameters: $D_i, C_{ij}, h_{ij}, S, w_i, W$, and w_e
2. Calculate the optimal reorder interval (T^*) at discount price interval j, starting from the lowest unit price.

   $$T^* = \sqrt{\frac{2s}{\sum_{i=1}^{n} D_i\ .(h_i\ .\ C_{ij} + w_e.E_e.t_x)}}$$

3. Calculate the optimal order quantity for each item i (Q_i^*).

   $$Q_i^* = T^* \times D_i$$

4. Check whether Q_i^* falls within the valid discount price interval j. If valid, proceed to Step 5. If not, repeat Step 2 using a different discount price interval.
5. Calculate the volume requirement for each item i (Qw_i^*).

   $$Qw_i^* = Q_i^* \times w_i$$

6. Check whether the total volume requirement of all items exceeds the warehouse capacity (W).

   $\sum_{i=1}^{n} Qw_i^* > W$

   If it does not exceed capacity, proceed to Step 10. If it does, proceed to Step 7.
7. Calculate the volume proportion of each item i (QwP_i^*).

   $$QwP_i^* = \frac{Qw_i^*}{\sum_{i=1}^{n} Qw_i^*}$$

8. Calculate the adjusted volume for each item i after considering warehouse capacity (QW_i^*).

   $QW_i^* = QwP_i^* \times W$
9. Convert the volume back to units to obtain the order quantity for each item i after capacity adjustment (Qg_i^*).

   $$Qg_i^* = \frac{QW_i^*}{w_i}$$

   Verify that Qg_i^* falls within the applicable discount price interval.
10. Calculate the reorder interval after warehouse capacity adjustment (G).

    $$G = \frac{\sum_{i=1}^{n} Qg_i^*}{\sum_{i=1}^{n} D_i}$$

11. Calculate TIC using G as the reorder interval.

    $$TIC = \sum_{i=1}^{n} C_{ij}.D_i + \frac{S}{G} + \frac{1}{2}\ \sum_{i=1}^{n} G.\ D_i.(h_i.C_{ij}\ + w_e.E_e.t_x)$$

III. RESULTS

A. Data Input

The model was tested using numerical data adopted from Silitonga and Moses for inventory parameters, and from Pramesti et al. [15] for carbon emission parameters. These data were adopted from previous studies and are used as a numerical illustration to validate the proposed mathematical model. Therefore, the data do not represent actual industrial data from a specific company. The use of reference data allows the proposed model to be compared directly with the reference model under the same experimental conditions. The inventory parameter data for each product are presented in Table I.

TABLE I. INVENTORY PARAMETER DATA

Parameter	Product 1	Product 2	Product 3
D_i	55,500	40,000	80,000
h_i	0.001	0.015	0.01
w_i	2.5	2	3
W		50,000	
S		235,000	

The all-unit discount policy applied by the supplier for each product is presented in Table II.

TABLE II. ALL-UNIT DISCOUNT POLICY

Item	Quantity Interval	Price (IDR/unit)
Product 1	Q < 9,000	13,000
	Q ≥ 9,000	12,000
	Q ≥ 15,000	11,000
Product 2	Q < 6,500	16,000
	Q ≥ 6,500	15,000
	Q ≥ 12,000	13,000
Product 3	Q < 13,000	9,000

Item	Quantity Interval	Price (IDR/unit)
	Q ≥ 13,000	8,000
	Q ≥ 21,000	7,000

The carbon emission parameters used in this study combine data from multiple sources. The average warehouse energy consumption (w_e) was adopted from Pramesti et al. [15] as a numerical illustration. The carbon emission factor (E_e) reflects Indonesia's grid emission factor based on official data from the Ministry of Energy and Mineral Resources (ESDM) 2021, while the carbon tax rate (t_x) follows the rate established under Indonesian Law No. 7 of 2021 on Harmonization of Tax Regulations (UU HPP). Thus, while (w_e) is illustrative, E_e and t_x represent actual regulatory values applicable in the Indonesian context. The carbon emission parameters used in this study are presented in Table III.

TABLE III. CARBON EMISSION PARAMETER DATA

Parameter	Value
w_e	1.14
E_e	0.000817
t_x	30,000

B. Numerical Result

Based on the model solution procedure, valid order quantities were obtained in the third iteration using the highest price level, with C1 = IDR 13,000, C2 = IDR 16,000, and C3 = IDR 9,000. The complete results of the model calculation are presented in Table IV.

TABLE IV. MODEL CALCULATION RESULTS

Parameter	Value
T^*	0.144
Qg_1^*	6,040
Qg_2^*	4,350
Qg_3^*	8,717
G	0.108
C_p	2,081,500,000
C_o	2,158,540
C_h	2,441,431
TIC	2,086,099,971

C. Model Comparison

To evaluate the effect of incorporating carbon emissions, a comparison of cost components between the reference model [14] and the developed model was conducted. The results are presented in Table V.

TABLE V. COST COMPONENT COMPARISON

Cost Component	Reference Model [14] (IDR)	Developed Model (IDR)
C_p	2,081,500,000	2,081,500,000
C_o	2,156,125	2,158,540
C_h	954,850	2,441,431
TIC	2,084,610,975	2,086,099,971

The purchasing cost (C_p) is identical in both models as unit prices and demand remain unchanged. The most significant difference occurs in the holding cost (C_h), where the developed model produces a substantially higher value due to the addition of the carbon cost component $w_e \times E_e \times t_x$ per unit. The total inventory cost of the developed model is IDR 1,488,996 higher than the reference model, entirely attributable to the increase in C_h from the carbon cost component. This difference represents the environmental cost of warehouse electricity consumption that has not been accounted for in conventional inventory models.

D. Sensitivity Analysis

Sensitivity analysis was conducted to examine the model's responsiveness to changes in parameters w_e, t_x and W, with variations of ±10%, ±20%, and ±30% from the base case values. The sensitivity analysis results for parameter w_e are presented in Table VI.

TABLE VI. SENSITIVITY ANALYSIS OF PARAMETER W_e

Variation	w_e	T^*	G	TIC
-30%	0.80	0.149	0.10887	2,085,939,811
-20%	0.91	0.148	0.10887	2,085,993,197
-10%	1.03	0.146	0.10887	2,086,046,584
0%	1.14	0.144	0.10887	2,086,099,971
10%	1.25	0.143	0.10887	2,086,153,357
20%	1.37	0.141	0.10887	2,086,206,744
30%	1.48	0.140	0.10887	2,086,260,131

The sensitivity analysis results for parameter t_x are presented in Table VII.

TABLE VII. SENSITIVITY ANALYSIS OF PARAMETER t_x

Variation	t_x	T*	G	TIC
-30%	21,000.00	0.149	0.109	2,085,939,811
-20%	24,000.00	0.148	0.109	2,085,993,197
-10%	27,000.00	0.146	0.109	2,086,046,584
0%	30,000.00	0.144	0.109	2,086,099,971
10%	33,000.00	0.143	0.109	2,086,153,357
20%	36,000.00	0.141	0.109	2,086,206,744
30%	39,000.00	0.140	0.109	2,086,260,131

The sensitivity analysis results for parameter W are presented in Table VIII.

TABLE VIII. SENSITIVITY ANALYSIS OF PARAMETER W

Variation	W	T^*	G	TIC
-30%	35,000	0.144	0.076	2,087,025,059
-20%	40,000	0.144	0.087	2,086,639,606
-10%	45,000	0.144	0.098	2,086,339,808
0%	50,000	0.144	0.109	2,086,099,971
10%	55,000	0.144	0.120	2,085,903,740
20%	60,000	0.144	0.131	2,085,740,214
30%	65,000	0.144	0.142	2,085,601,846

The sensitivity analysis results show that parameters w_e and t_x produce identical patterns in T^*, G, and TIC. This occurs because w_e and t_x always appear together as a single multiplicative block $w_e \times E_e \times t_x$ in the formulas for T^* and C_h, making it impossible for the model to distinguish their individual effects. An increase in either w_e or t_x causes T^* to decrease and TIC to increase, while G remains unchanged as warehouse capacity is assumed constant. Parameter W has the greatest influence on TIC compared to w_e and t_x. At a +30% variation, a change in W reduces TIC by IDR 498,125, while changes in w_e or t_x only alter TIC by IDR 160,160. Overall, all parameters are not sensitive to TIC within the ±30% variation range, consistent with the findings of the reference model [14]. This insensitivity is primarily driven by the dominance of the purchasing cost (C_p) in the total inventory

 EISSN: 2961-872X ●PISSN: 2961-8924●DOI: 10.56741/IISTR.esl.002319

cost structure. C_p accounts for the majority of TIC and remains constant across all parameter variations since unit prices and demand are fixed. As a result, even substantial changes in w_e, t_x, or W produce only marginal effects on TIC relative to its total magnitude.

These findings indicate that the proposed inventory model is relatively robust to moderate variations in warehouse-related parameters. From a managerial perspective, changes in electricity-related factors and operating time may affect the optimal replenishment cycle, but they are unlikely to substantially alter the overall inventory cost under the current cost structure. The greater influence of , however, suggests that warehouse capacity decisions deserve comparatively greater managerial attention. Nevertheless, because purchasing cost dominates TIC, cost-reduction strategies focused solely on warehouse operations may yield limited financial benefits. More substantial cost improvements may therefore require simultaneous consideration of purchasing policies, supplier negotiations, demand management, and warehouse efficiency.

IV. Conclusion

This study developed a multi-item EOQ inventory model that integrates all-unit discounts, warehouse capacity constraints, and carbon emissions as explicit cost components. The carbon cost variable, calculated as the product of average warehouse energy consumption, the carbon emission factor, and the carbon tax, was incorporated into the holding cost equation and the optimal reorder interval formula of the reference model [24]-[26]. In this research, the formula refers to Silitonga and Moses [14]. The developed model yields an optimal cycle time T^* = 0.144 periods, order quantities of Qg_1^* = 6,040 units, Qg_2^* = 4,350 units, and Qg_3^* = 8,717 units, a capacity-adjusted reorder interval G = 0.108 periods, and a total inventory cost of IDR 2,086,099,971 per planning period.

The addition of carbon emission variables affects the mathematical structure of the model in two ways. First, the carbon cost component $w_e \times E_e \times t_x$ enlarges the denominator of the optimal reorder interval formula, resulting in a smaller T^* and lower order quantities per cycle compared to the reference model. Second, the same component increases the per-unit holding cost, which raises the total holding cost and consequently the total inventory cost by IDR 1,488,996 relative to the reference model. Sensitivity analysis further reveals that all parameters remain insensitive to total inventory cost within a ±30% variation range, with warehouse capacity having the greatest influence on total cost among the parameters examined. These findings confirm that integrating carbon emissions into inventory models produces measurable economic effects while maintaining model robustness. Future research may extend this framework by incorporating probabilistic demand to better represent real-world inventory conditions.

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 EISSN: 2961-872X ●PISSN: 2961-8924●DOI: 10.56741/IISTR.esl.002319