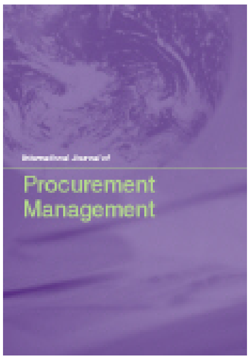

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Sustainable inventory model for price and credit-dependent demand with carbon emissions cap and trade

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Abstract: This presented article considers sustainable inventory policies and trade credit. Demand varies because of the trade credit period and selling price provided by retailers to consumers. Under the carbon cap-and-trade and carbon tax protocols, it is also affected by environmental sensitivity due to carbon emissions generated by consumers. Therefore, in this article, demand is dependent on selling price, credit period, and total carbon emissions. Decision inventory models are created under three different cases: without regulations, with carbon tax regulation, and with carbon cap-and-trade regulations. Then the obtained results are analysed using the numerical examples to validate the proposed model. Using sensitivity analysis, graphs are presented to check the outcome of parameters on the defined decision variables. The report concludes with its findings and a prediction for potential future research.

Keywords: trade credit; carbon tax regulations; CT regulations; carbon cap-and-trade regulations; CCAT regulations.

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1 Introduction

The major contributor to global warming is carbon emissions (CE) which get more attention and agreement worldwide. Nowadays, sustainable development has become a major issue all over the world which is a key concern of the economy. As we know, sustainability goals are to minimise the negative effects on the surroundings and protect the depletion of natural resources. It is a fundamental idea and approach that aims to satisfy the current and future demands without affecting the future generations' capacity to fulfil their demand. It is concerned with the remarkable balance among the social, environmental, and economic factors to promote the long-standing well-being of people and the planet as well. Therefore, development in the way to obtain sustainability becomes the main goal for an increasing economy. The fundamental priority of the economy is sustainable development. Governments are facing increasing pressure to pass legislation to reduce the volume of all these emissions. Different governments implement different policies to reduce the increase of CE in the atmosphere for sustainability. Some governments implement one of these policies say carbon tax (CT) policy, in which a fixed tax is levied across carbon dioxide emitting units. Another regulation to reduce carbon discharges is the CCAT regulation in which companies under this regulation receive the free CE cap for a fixed time interval and trade these caps in similar trade marketplace with other companies.

The firms have to optimise and regulate their actions to reduce the carbon discharge, as well as react to the regulations. Traditional methods are predicated on the implicit assumption that payment for items would be given to the provider immediately after delivery. However, in regular business deals, it is becoming more common for suppliers to allow retailers to pay later, which is known as the trade credit period. It is commonly employed by businesses for short-term funding. Before the trade credit term expires, the seller can trade the products, receive income, and get interest. The seller settles the payment during the stipulated credit timeframe as offered by the supplier. However, the supplier bears the risk of whether the seller will pay the money within the given credit period. Trade credit terms provide the retailer with the flexibility to place larger product orders with the supplier when the retailer does not have enough money to buy products for sale. Suppliers find this credit period strategy advantageous, as it not only stimulates increased purchasing from existing customers but also attracts new buyers, serving as an effective alternative to price reductions. As a result, suppliers frequently employ these forms of policies to market their products.

1.1 Literature review

The first mathematical economic order quantity (EOQ) model was proposed by Goyal (1985) in which the concept is instituted within acceptable payment delay conditions, prompting numerous researchers to embark on developing inventory models that account for the effects of permissible payment delays. This EOQ model is an extension of the classical EOQ model. Chu et al. (1998) took the initiative to broaden this model by additionally applying the deterioration of the products in which the total cost function was optimised. Huang (2003) also extended the model of Goyal (1985) by introducing a two-level trade credit system, wherein both the supplier and retailer allowed delay periods for the retailer and their customers, respectively. The replenishment rate of the model proposed by Goyal (1985) was infinite and Chung and Huang (2003) extended that model with a finite replenishment rate. Huang (2007) proposed a model by assumes the trade credit duration offered to retailers by suppliers is always greater than a trade credit that is given by retailers to customers, which incorporates both Huang's (2003) and Chung and Huang's (2003) models. In the model proposed by Huang and Hsu (2008), they expanded the assumption that the supplier provides complete trade credit to the retailer, and in turn, the retailer offers it to their customers. They developed two easy-to-use theorems for determining the retailer's optional inventory policy. Kreng and Tan (2010) proposed a two-level trade credit policy that depends upon the order quantity. They determined the decisions of optimal replenishment where a two-level trade policy applied with ordered quantity is not less than the predetermined quantity after Kreng and Tan (2011) analysed the effect of wholesaler's decisions for optimal replenishment while considering the finite replenishment rate and defective quality of the product. Mahata (2012) assumed that the significant decision-making authority is maintained by a retailer, where the retailer offers a comprehensive trade credit period extended by the supplier, while concurrently granting customers a partial trade credit period. In this scenario, the retailer gets the best benefits. Min et al. (2012) presented an article in which the demand is dependent on the level of inventory, where the payment is not instantaneous, but it's a delayed payment. In contrast, Soni (2013) explored the optimal replenishment strategy for retailers in the context of trade credit, taking into account factors such as demand dependency on inventory levels and pricing, where delayed payment played a significant role. Giri and Maiti (2013) considered demand as a credit and price dependent in the study of financing the product through trade credit. The lot-sizing rules for deteriorating and imperfect goods with trade credit and time-dependent demand are examined by Tiwari et al. (2017). When the cash discount depends on the timing and ordering quantity for the customer and the retailer respectively, Chung et al. (2018) proposed a combination of trade credits, quantity discounts, and cash discounts to study an inventory model. The analytical techniques in the mathematical model considering two-level trade credit to determine the optimal ordering strategy were analysed by Liao et al. (2018). In the model presented by Mishra et al. (2019), a trade credit policy on remanufactured products was analysed. They presented the system of deteriorating inventory with stock and selling-price-dependent demand while optimising cycle time and selling price. Gautam et al. (2020) examined a model of sustainable production policies under the impact of volume agility, preservation technology, and price-reliant demand. In the notable research conducted by Banu and Mondal (2020), an uncertain inventory model tailored for deteriorating items within the context of a two-level trade credit system, taking into account the influence of customers' credit periods on demand. Notably, they introduced a novel class of fuzzy numbers, referred to as 'q-fuzzy numbers', which encompasses both linear and nonlinear membership functions simultaneously. In Mondal and Giri's (2022) study, they introduced a two-level sustainable supply chain model, wherein the demand is contingent upon the selling price and the environmentally responsible practices undertaken by both entities within the supply chain. They formed four mathematical models under different scenarios of cap-and-trade policy: retailer-led revenue sharing, centralised, decentralised, and revenue sharing on bargaining. In the realm of credit-dependent demand, Mahato and Mahata (2021) formulated a robust inventory management framework for deteriorating items, featuring a two-level trade credit system. This model is designed to accommodate the dynamic fluctuations in the demand rate, which is contingent on both the product's freshness condition and the specific credit period extended to potential customers. Mandal et al. (2021) presented a model under the trade credit period where demand is advertising and stock-level dependent. The model is worked with assuming a finite rate of replenishment. Singh et al. (2021) analysed the two-echelon supply chain with two-level-trade-credit policies considering supplier and producer. The main aim was to optimise total cost where the total cost function was scrutinised in two cases: with trade-credit-dependent demand and with selling price-dependent demand. Jiang et al. (2022) studied the model working between a well-funded supplier and another small-sized retailer while considering capital constraints. They demonstrate that bank financing is always advantageous to retailers, but supplier choices are influenced by two important factors. Fu et al. (2022) developed a supply chain model that shows the trade credit impact on information sharing. They show the effect of trade credit offered by manufacturers to suppliers. Taleizadeh et al. (2022) proposed a sustainable model where demand is price and CE amount sensitive. They considered partial trade credit and shortages with partial backlogging. The main objective is to maximise total profit by applying signomial geometric programming global optimisation. A Stackelberg game-theoretic approach is applied in the Hovelaque et al. (2022) model where a non-cooperative game for a supplier, a retailer, and a bank is analysed and demand is taken as price sensitive. Trade credit can also be provided by both suppliers and retailers to buyers. This scenario in a model of newsvendor is analysed by Wang et al. (2022) by taking credit-dependent demand and optimising trade credit. They compared credit and price contracts and proposed that both are alternatives.

1.2 Research gap

Substantial research has been conducted separately on two distinct areas of inventory management: the production-inventory model involving trade credit and the production-inventory model taking into account CE regulations. However, there is a notable gap in the existing literature where these two research streams have not been effectively integrated to examine the optimal strategies for production and trade credit policies in the context of both CE regulations and environmental consumer awareness. The initial body of research primarily operates under the assumption that demand is contingent upon the credit period, neglecting the impact of customer environmental consciousness on demand and the consequences of CE regulations on enterprise costs. Conversely, the second research stream focuses on demand primarily being influenced by CE concerns and does not factor in the effects of trade credit on demand patterns and default risk.

To bridge this research gap, the present study delves into inventory models that incorporate trade credit aspects while also factoring in the influence of CE policies and consumer environmental sensitivity. The aim is to elucidate optimal strategies for both credit and inventory management in this multifaceted context, where environmental concerns and regulatory compliance intersect with traditional trade credit and inventory considerations.

This paper is constructed in the following manner. In Section 2, the notations and assumptions for the whole paper are mentioned. In Section 3, the mathematical model considering the profit function in three scenarios is discussed:

1 without any carbon regulation policy

2 CT regulations

3 carbon cap-and-trade (CCAT) regulations.

Section 4 provides numerical analysis and optimal solutions to validate the whole mathematical model. In Section 5, some managerial insights are given to get some results. In Section 6, the conclusion is presented.

2 Notations and assumptions

The mathematical inventory model is established based on the following notations and assumptions.

2.1 Notations

Inventory parameters	
$R(N, p, Q)$	Demand of the market (units)
$CQ_2(Q)$	Total carbon emissions (units)
Cost parameters	
A	Seller's ordering cost (\$/order)
h	Seller's holding cost (\$/unit/month)
c	Seller's purchase cost (\$/unit)
f_b	Seller's transportation cost (\$/unit)
Inventory parameters related to CE	
A_{CE}	Carbon emissions associated per unit order (\$/unit/order)
h_{CE}	CE associated per unit stored in inventory (\$/unit/month)
C_{PvCE}	CE associated per unit produced or purchased (\$/unit/month)
f_{bCE}	CE associated per unit transform (\$/unit/month)
C_T	Tax rate of CE (\$/ton units)
C_c	CE cap
C_p	CE per unit trade price (\$/ton units)
Decision variables	
N	Trade credit period offered by retailer to the consumers (month)
P	Seller's selling price (\$/unit)
Q	Seller's replenishment quantity (units)

2.2 Assumptions

1. The retailer provides the trade credit period to its customers.
2. Demand is a function of the selling price, trade credit period, and CE which is represented as $R(N, p, Q) = \alpha + \delta N - \eta p - \gamma CQ_2(Q)$, where $\alpha > 0$ denotes the scaling demand factor, $\delta > 0$ is a fixed credit period elasticity which governs the increasing demand rate concerning the credit period, $\eta > 0$ denotes price elasticity with $\eta \ll \alpha$ and $\gamma > 0$ denotes carbon emissivity due to which demand is decreasing with increasing CE.
3. When a retailer gives a credit period to a consumer, the retailer encounters the credit risk associated with customers' potential inability to fulfil their debt obligations. A higher credit duration may lead to greater default risk which increases the possibility that the retailer will not be able to get all receivables. The rate of default risk that will increase with credit duration is expressed using an exponential method $F(N) = 1 - e^{-kN}$, where $k > 0$ is default risk elasticity (Qin et al., 2015).
4. The opportunity cost for the retailer of receivables delivered in a given credit period is expressed as e^{-jN}, where $j > 0$ denotes opportunity cost interest (Qin et al., 2015).
5. There is instantaneous replenishment.
6. Shortages are not permitted.
7. The cap on CE is set without taking the impact of time into account since the decisions are taken in one period rather than multiple periods.

3 Mathematical model

The total CE of the retailer is represented as CQ_2. The replenishment time for purchasing quantity is represented as $\frac{R(N, p, Q)}{Q}$. The holding cost is represented as $\frac{Q}{2}$. Hence, the respective CE associated with holding inventory and purchasing inventory is $\frac{h_{CE}Q}{2}$ and $\frac{A_{CE}R(N, p, Q)}{Q}$. The amount of CE during the producing inventory is $C_{PvCE}R(N, p, Q)$ and the transportation is $f_{bCE}Q$. Hence, the amount of total CE generated through holding, purchasing, producing, and transporting inventory is represented as:

$$CQ_2(N, p, Q) = \frac{A_{CE}R(N, p, Q)}{Q} + C_{PvCE}R(N, p, Q) + \frac{h_{CE}Q}{2} + f_{bCE}Q$$

The product's market demand is mainly dependent on CE, selling price, and credit period. In this paper, the outcome of CE on the demand is considered using total CE. Therefore, the demand function is represented by

$$R(N, p, Q) = \alpha + \delta N - \eta p - \gamma CQ_2.$$

The different costs relative to this model are as follows:

a Ordering cost $OC = \frac{A}{2}\left(\frac{2\alpha + 2\delta N - 2\eta p - \gamma Q h_{CE} - 2\gamma f_{CE} Q}{Q + \gamma C_{PvCE} + \gamma A_{CE}}\right).$

b Holding cost $HC = \frac{hQ}{2}.$

c Producing cost $PC = \frac{cQ}{2}\left(\frac{2\alpha + 2\delta N - 2\eta p - \gamma Q h_{CE} - 2\gamma f_{CE} Q}{Q + \gamma C_{PvCE} + \gamma A_{CE}}\right).$

d Transportation cost $FC = f_b Q.$

e Sales revenue by considering opportunity cost and default risk
$SR = \frac{pe^{-(j+k)N} Q}{2}\left(\frac{2\alpha + 2\delta N - 2\eta p - \gamma Q h_{CE} - 2\gamma f_{CE} Q}{Q + \gamma C_{PvCE} + \gamma A_{CE}}\right).$

Case 1: without any carbon policy regulation

The total profit without regulations is expressed by

$$\begin{aligned} TP_1 &= SR - OC - HC - PC - FC \\ &= \left(\frac{2\alpha + 2\delta N - 2\eta p - \gamma Q h_{CE} - 2\gamma f_{CE} Q}{2(Q + \gamma C_{PvCE} + \gamma A_{CE})}\right)\left[pe^{-(j+k)N} Q - A - cQ\right] - \left(\frac{h}{2} + f_b\right) Q. \end{aligned} \quad (1)$$

Case 2: under CT regulation

The total profit under CT regulations is expressed by

$$\begin{aligned} TP_2 &= SR - OC - HC - PC - FC - C_T CQ_2 \\ &= \left(\frac{2\alpha + 2\delta N - 2\eta p - \gamma Q h_{CE} - 2\gamma f_{CE} Q}{2(Q + \gamma C_{PvCE} + \gamma A_{CE})}\right)\left[pe^{-(j+k)N} Q - A - cQ\right] - \left(\frac{h}{2} + f_b\right) Q \\ &\quad - C_T\left[\left(\frac{A_{CE}}{Q} + C_{PvCE}\right)\left(\frac{2\alpha + 2\delta N - 2\eta p - \gamma Q h_{CE} - 2\gamma f_{CE} Q}{2(Q + \gamma C_{PvCE} + \gamma A_{CE})}\right) + \left(\frac{h}{2} + f_b\right)\right] Q. \end{aligned} \quad (2)$$

Case 3: under CCAT regulation

The total profit under CCAT regulations is expressed by

$$\begin{aligned} TP_3 &= SR - OC - HC - PC - FC + C_p\left(C_c - CQ_2\right) \\ &= \left(\frac{2\alpha + 2\delta N - 2\eta p - \gamma Q h_{CE} - 2\gamma f_{CE} Q}{2(Q + \gamma C_{PvCE} + \gamma A_{CE})}\right)\left[pe^{-(j+k)N} Q - A - cQ\right] \\ &\quad - \left(\frac{h}{2} + f_b\right) Q - C_p\left(C_c - \left[\left(\frac{A_{CE}}{Q} + C_{PvCE}\right)\left(\frac{2\alpha + 2\delta N - 2\eta p - \gamma Q h_{CE} - 2\gamma f_{CE} Q}{2(Q + \gamma C_{PvCE} + \gamma A_{CE})}\right)\right.\right. \\ &\quad \left.\left. + \left(\frac{h}{2} + f_b\right)\right] Q\right). \end{aligned} \quad (3)$$

In these mathematical models, credit period N, replenishment quantity Q, and selling price p are decision variables.

4 Numerical analysis

This section provides numerical examples that illustrate our inventory methodology and outcomes. The main purpose of this proposed model is to maximise the total profit. This is obtained by the subsequent steps.

Step 1 Differentiate the equations (1), (2), and (3) partially concerning decision variables N, p and Q.

Step 2 Assign all inventory parameters to their values except decision variables.

Step 3 Compare all these equations of partial derivatives by taking all equal to zero.

Step 4 To get the solution, solve these equations using mathematical software.

Step 5 Using concavity, scrutinise the optimality of the total profit.

In this article, three models with different carbon regulation policies are scrutinised. The following hypothetical data values are considered to check the model.

$$\alpha = 100, \delta = 70, A = 100, h = 115, c = 10, f_b = 4, A_{CE} = 15, h_{CE} = 1, C_{PvCE} = 0.4,$$
$$f_{bCE} = 0.8, \gamma = 0.03, \eta = 0.6, j = 0.4, k = 0.05, C_T = 1.33, C_p = 0.33, C_c = 900.$$

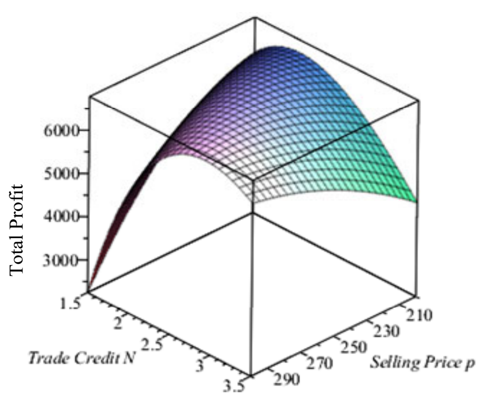
The solutions obtained by these parameters using Maple 18 are shown in the table.

Table 1 Solution of three different carbon policies using Maple 18

	Credit period (in month)	*Selling price (in \$)*	*Replenishment quantity (in units)*	*Total profit (in \$)*
Case 1	2.58	259.26	15.45	6,785.66
Case 2	2.54	259.26	16.25	6,546.70
Case 3	2.57	259.26	15.66	7,022.45

The graphical representation is confirmed in Maple 18 as follows using the inventory parameters and optimal solution presented in Table 1.

Figure 1 Concavity of total profit w.r.t. trade credit and selling price (see online version for colours)



4.1 Case 1

Figure 2 Concavity of total profit w.r.t. selling price and replenishment quantity (see online version for colours)

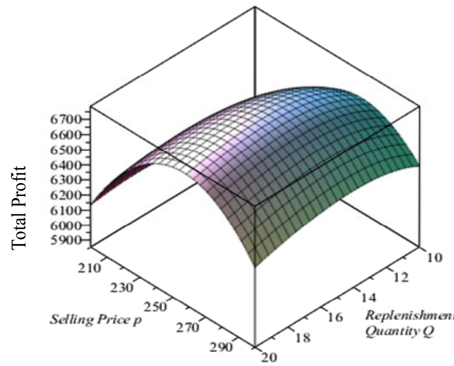


Figure 3 Concavity of total profit w.r.t. trade credit and replenishment quantity (see online version for colours)

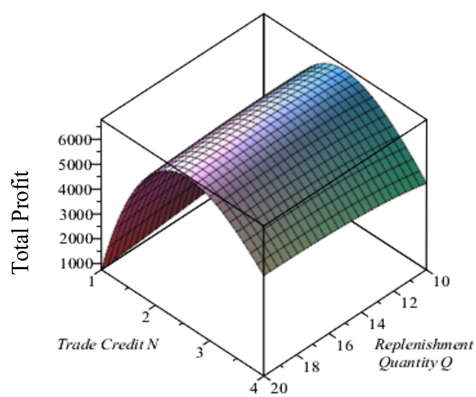
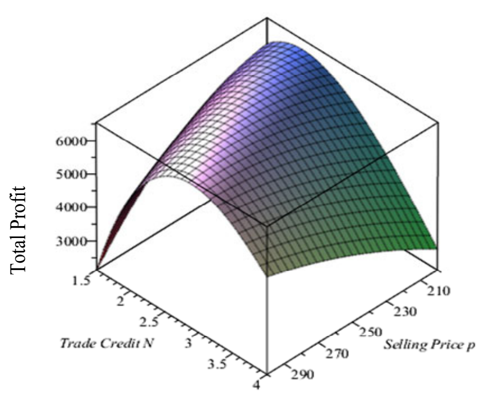


Figure 4 Concavity of total profit w.r.t. trade credit and selling price (see online version for colours)



4.2 Case 2

Figure 5 Concavity of total profit w.r.t. trade credit and replenishment quantity (see online version for colours)

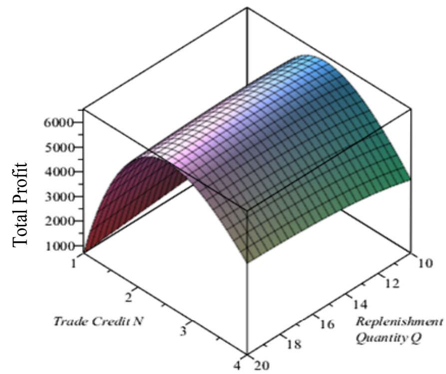


Figure 6 Concavity of total profit w.r.t. selling price and replenishment quantity (see online version for colours)

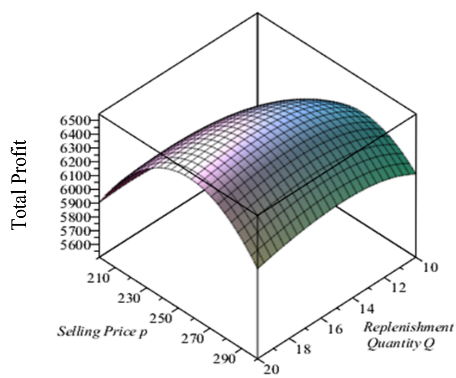
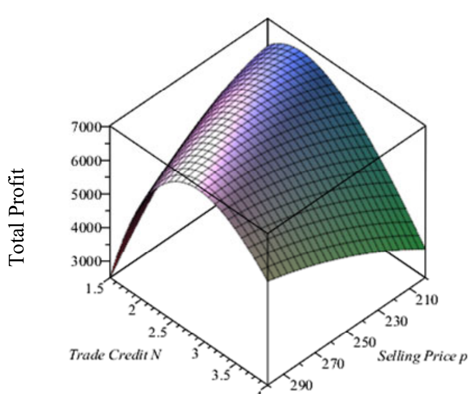


Figure 7 Concavity of total profit w.r.t. trade credit and selling price (see online version for colours)



4.3 Case 3

Figures 1–3 represent the scenario in the absence of any regulations on CE, denoting the baseline condition. Figures 4–6 depict the outcomes under CT regulations, where a specific tax is imposed on CE. Figures 7–9 illustrate the results when carbon cap-and-trade regulations are implemented, indicating a system where emission allowances are allocated and tradable.

Through analysis and optimisation of the decision variables within these figures, it is demonstrated that the total profit is maximised, as determined by the optimised values of these decision variables.

Figure 8 Concavity of total profit w.r.t. trade credit and replenishment quantity (see online version for colours)

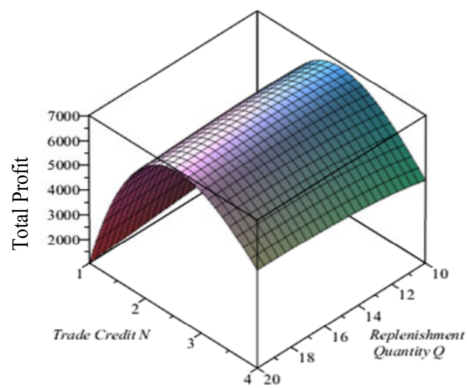
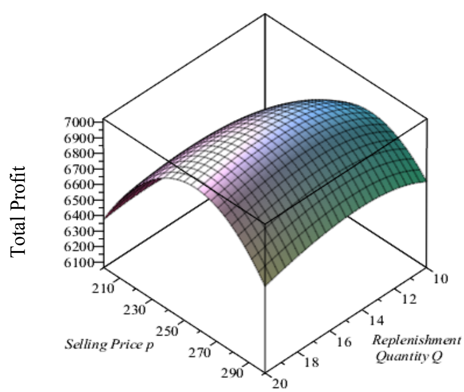


Figure 9 Concavity of total profit w.r.t. selling price and replenishment quantity (see online version for colours)



5 Managerial insights

Figure 10 presents a comparative analysis of total profit across various regulatory models. It demonstrates that in the absence of CE regulation, total profit is higher than when subjected to CT regulations. However, this higher profit comes at the expense of sustainability. When CT regulations are in effect, total profit is lower than under CCAT regulations, with a notable increase of 7.27% relative to the CT policy. Nonetheless, a careful examination of these three scenarios reveals that the CCAT regulatory approach is the most advantageous for the retailer in terms of profitability while concurrently upholding sustainability standards.

Figure 10 Total profit w.r.t different models (see online version for colours)

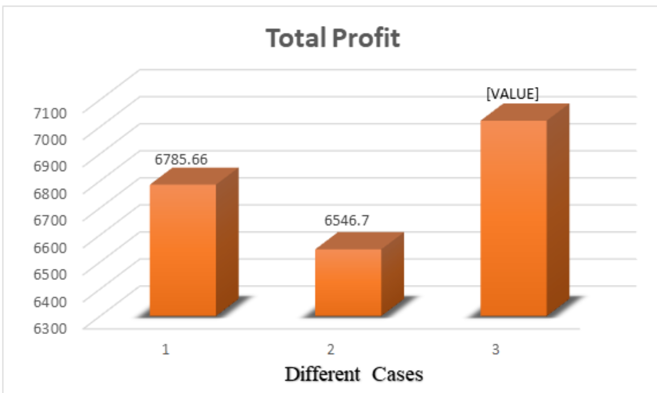


Figure 11 Replenishment quantity with respect to changes in different inventory parameters (see online version for colours)

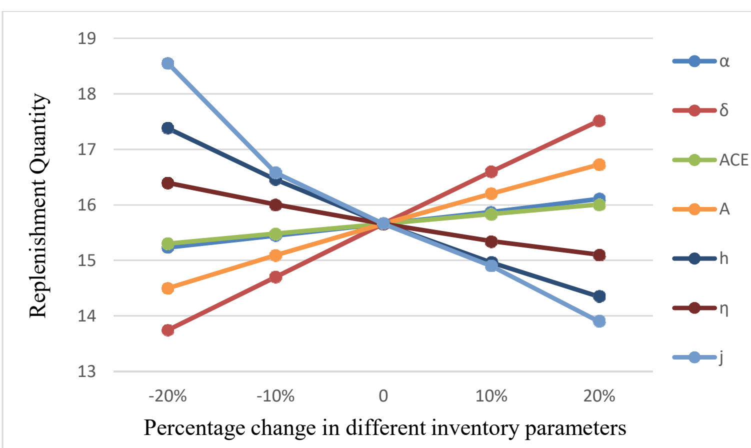


Figure 11 presents alterations in the replenishment quantity as different inventory parameters are modified by a fixed percentage. This figure illustrates that certain parameter increases result in an augmented replenishment quantity, while others lead to a reduction in replenishment quantity. Notably, the seller's replenishment quantity exhibits a strong sensitivity to changes in opportunity cost interest and credit period elasticity.

Figure 12 Credit period with respect to changes in different inventory parameters (see online version for colours)

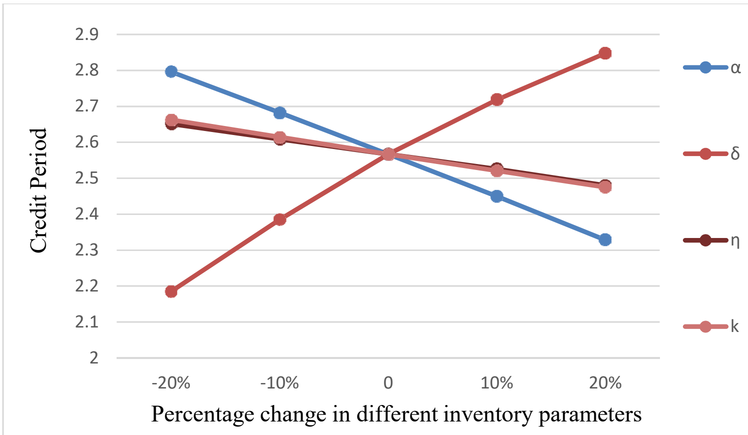


Figure 12 illustrates variations in the trade credit period in response to alterations in various inventory parameters. Specifically, the trade credit period extends when the credit period elasticity increases, whereas it contracts when the seller's ordering cost, price elasticity, and default risk elasticity exhibit rising values. Furthermore, an increase in scale demand leads to a decrease in the trade credit period, a phenomenon that can mitigate the retailer's default risk.

Figure 13 Selling price with respect to changes in different inventory parameters (see online version for colours)

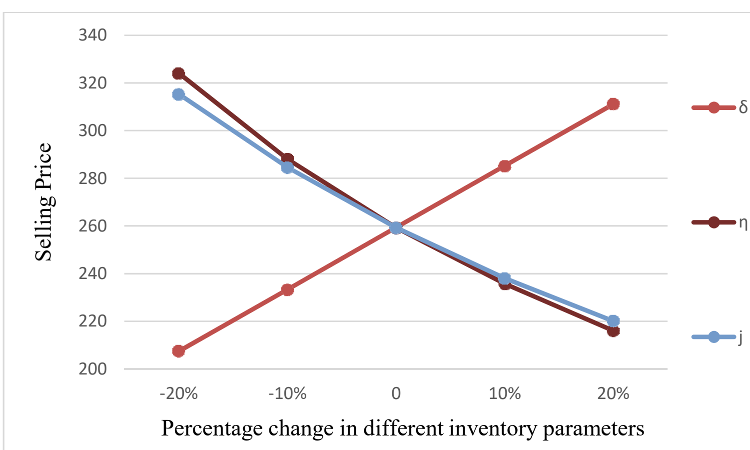


Figure 13 depicts the fluctuation in the selling price, driven by alterations in inventory parameters. Selling price variations are influenced solely by changes in credit period elasticity, price elasticity, and the interest rate associated with opportunity cost. Specifically, the selling price escalates as the credit period elasticity increases, while it declines in response to escalating values of price elasticity and the interest rate related to opportunity cost.

Figure 14 Total profit with respect to changes in different inventory parameters (see online version for colours)

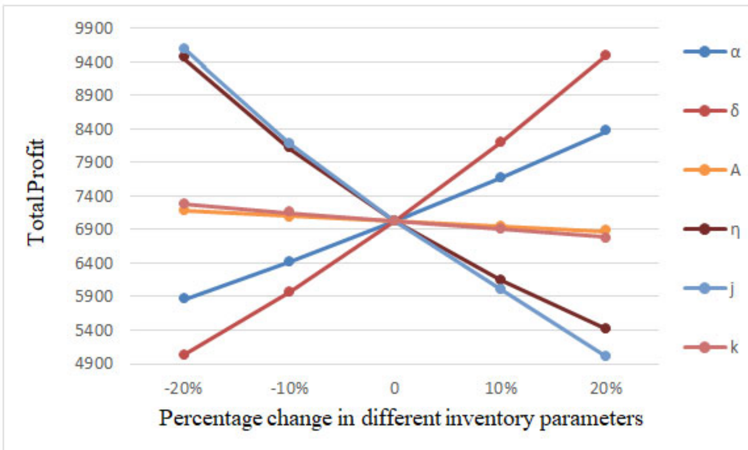
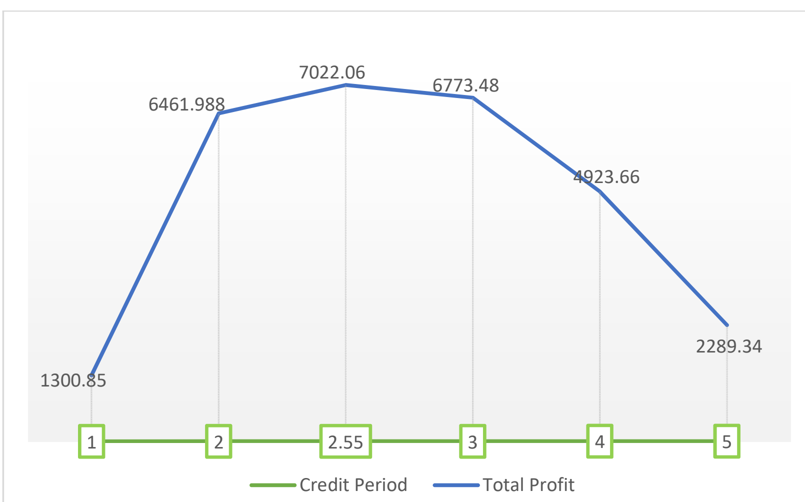


Figure 15 Total profit with respect to different credit periods (see online version for colours)



In Figure 14, we analyse the impact of various inventory parameters on the total profit function. Certain parameters exhibit a positive influence on total profit, while others demonstrate a negative impact. Specifically, the scale of demand and the elasticity of the credit period exhibit a positive effect on the total profit function. Conversely, the seller's ordering cost, price elasticity, opportunity cost interest rate, and default risk elasticity exert a negative influence on the total profit function. To elaborate, an increase in scale demand leads to higher profits for retailers due to increased product sales.

Figure 15 illustrates the relationship between total profit and the trade credit period. At the point of the optimal credit period, total profit reaches its maximum value. Deviating from this optimal period, whether by increasing or decreasing the credit period, results in a reduction in total profit. This observation signifies that the supplier's profit diminishes when the credit period is excessively long or excessively short.

6 Conclusions

In this proposed model, the main goal is to maximise the total profit by identifying the optimal trade credit period, selling price, and replenishment quantity under three different scenarios says the model without any CE regulations, under CT regulations, and under CCAT regulations where demand is CE, selling price and trade credit period dependent function. The sensitivity analysis of total profit, selling price, trade credit period, and replenishment quantity with respect to different parameters say scale demand, carbon emissivity, different parameters of cost, and additional inventory parameters throws light on the practical implication and validation of this proposed model. A numerical illustration is provided to elucidate and enhance the optimisation processes. In the presented three scenarios, the highest total profit is obtained under the CCAT regulations which regulation is more beneficial in this type of production system. Total profit is very much positively affected by δ whose increasing value leads to increasing total profit. This presented inventory model can be further expanded for future research. This model is extended by applying shortages. Also using a fuzzy environment, this model can be extended. Trade credit for three stages can also be applied. Additionally, demand can also be taken as time-dependent.

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