

# Pricing and Carbon Emission Reduction Decisions in a Dual-Channel Supply Chain

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**Abstract**— Due to the importance of environmental issues, customers prefer to buy low-carbon products and have an Eco-friendly behavior. Manufacturers produce the substitutable product under cap-and-trade regulations. Two chains are in-competite on a product's green level, which is determined by the manufacturer. In some cases, firms have difficulties in providing sufficient capital to buy extra carbon emission quotas which force them to take loans from the banks. In this study, a two-echelon dual-channel supply chain consisting of one manufacturer and one retailer have been studied and a Stackelberg game is implemented on vertical and horizontal approaches. Various metaheuristic and hybrid metaheuristic methods are applied to optimize the revenue based on optimal decision variables such as retailer prices, carbon emission reduction rate, bank interest rate, and wholesale price. Performance of the applied methods are compared which determines the best algorithm in each case.

## I. INTRODUCTION

Environmental concerns have become increasingly important for consumers when purchasing products. They are more likely to choose products that are eco-friendly or locally sourced in an effort to minimize the impact on the environment. In order to encourage companies to adopt more sustainable practices, governments have implemented various regulations and policies, such as the cap-and-trade system. This system provides a financial incentive for companies to reduce their emissions and thus contribute to environmental protection. Additionally, online systems have revolutionized supply chain management, making it easier for retailers and suppliers to reach customers through e-commerce platforms. With the increasing demand for sustainable products, it is important for companies to implement environmentally conscious strategies in order to remain competitive in the market. This paper explores the use of the cap-and-trade system and online systems to promote sustainability in the supply chain, and how companies can leverage these tools to meet customer demand and maintain profitability.

Du et al used game theory to analyze two types of supply chains: one operating in a cap-and-trade system and the other with a consumer preference for low carbon products. Both studies focused on the equilibrium strategies and profits of the supply chain members under different scenarios. [1],[2]. Li et al investigated the pricing policies of a competitive dual-channel green supply chain, consisting of a traditional retail channel and an online channel. The authors proposed a game-theoretical model to capture the interactions among the supply chain members, including the manufacturer, the traditional retailer, the online retailer, and the consumers. The study

focused on the pricing strategies of the members and their impacts on the profits and social welfare. The results showed that a coordinated pricing strategy could increase the profits of the supply chain members and improve social welfare[3]. Xu et al. investigated production and pricing decisions in a make-to-order supply chain under cap-and-trade regulation. They proposed a model to analyze the interactions among the manufacturer, supplier, and retailers. A coordinated approach was suggested to balance emissions reduction and profit maximization [4]. Qian et al studied channel coordination in a two-echelon sustainable supply chain with a fair-minded retailer under cap-and-trade regulation. Coordination issues could arise due to the retailer's fairness concern, and the authors suggested profit sharing and price discounts to promote coordination [5]. Taleizadeh et al investigated pricing and coordination strategies in a dual-channel supply chain with green production under cap-and-trade regulation. The authors analyzed the optimal decisions of the decentralized and centralized models and suggested a wholesale price subsidy as a coordination mechanism[6]. [7] , [8], [9] proposed a green supply chain and studied the location routing and inventory problems with simultaneous pick-up and delivery. [10], [11] proposed a novel robust control chart for monitoring multiple linear profiles in phase II, introduces a robust monitoring method of simple linear profiles using M-estimators. Alizadeh et al proposes an inexact variance-reduced method for stochastic quasi-variational inequality problems with an application in healthcare [12]. Saraei et al utilized statistical analysis techniques on system parameters to determine the most favorable factor for an experiment [13].

The focus of this research is on a two-echelon supply chain, consisting of a manufacturer and a retailer, that produces a substitutable product under cap-and-trade regulations. The manufacturer sells the product via retailer and an online platform. The study examines both decentralized and centralized supply chain approaches, where members aim to maximize their own profit or the profit of the entire chain, respectively. Additionally, the research incorporates the use of bank loans and carbon emission trading markets as additional factors. The contribution of this study lies in its comprehensive analysis that includes various economic and environmental factors. The proposed mathematical model in this research is solved using a game theory approach and a metaheuristic combination to achieve a more efficient solution. The combination of these approaches allows for a more robust analysis of the complex supply chain system under various scenarios.

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## II. PROBLEM DESCRIPTION

In this research, a two-echelon supply chain consisting of one manufacturer and one retailer have been studied. Manufacturers produce the substitutable product under cap-and-trade regulations. The manufacturer not only sells the product to the retailer but also sells directly to the end customer via online platform. The manufacturer sells the product to the retailer at a wholesale price  $p_j$ , then the Eco-friendly customers can purchase their product directly from the firm through the online channel at price  $p_1$  or provide it from the retailer at a retail price of either. Government charges every firm up to  $G$  quotas, they can decide about buying/selling their quotas in the carbon emission trading market when they face surplus/lack quotas. In some cases, firms have difficulties in providing sufficient capital to buy extra carbon emission quotas that drive them to take a loan from a bank. For the simplicity of the model, it is assumed there is one period. Before the beginning of the period, if firms need capital for providing their shortage of carbon emission quotas, they take a loan from bank at the interest rate of return, but in case of having a surplus of quotas, it's like firms invest their extra quotas capital in bank for one period at an interest rate of return.

In this research, the decentralized and centralized supply chain has been discussed, respectively. In a decentralized supply chain, there is a two-stage Stackelberg game where the manufacturer is leader and retailer is a follower. At first, the manufacturer decides the optimal greening level (carbon emission reduction rate), the wholesale price and online price and then the retailer based on the manufacturer's optimal decision takes an optimal measurement on retailer price. Both members of this chain try to maximize their own profit, and they do not focus on the supply chain's profit. In centralized chain, members consider as an integrated system that they keen on the increasing profit of total chain. A decision like carbon emission reduction, retailer price, and the online price will make by the manufacturer because, in this approach, we think the manufacturer is powerful enough to adopt the optimal solution for the whole chain. Symbols and notations used through the paper are discussed in Table I. The subscript ' $i$ ' denotes the supply chain  $i$ .

Table I. Notations

Notation	Detail
$a_i$	Initial market potential demand supply chain $i$ through the traditional channel
$a_{0i}$	Initial market potential demand supply chain $i$ through the online channel
$d_{ir}$	The demand for supply chain $i$ through the traditional channel
$d_{i0}$	The demand for supply chain $i$ through the online channel
$\lambda_i$	Demand sensitivity coefficient to the rival greening level. (Product greening level competition degree), $0 < \lambda < 1$
$K$	Carbon trading price of unit product
$e$	Initial carbon emission of unit product
$m$	Cost coefficient of emissions reduction investment
$E_i$	The total quantity of carbon trading of supply chain $i$
$G$	Total carbon quota from the government
$\beta_i$	own price elasticity for demanding $i$ in traditional channel

$\beta_{0i}$	own price elasticity for demanding $i$ in the online channel
$\gamma_i$	Price elasticity for the demand of product $i$ with respect to the selling prices of the product in traditional competitive channel.
$\gamma_{0i}$	Price elasticity for the demand of product $i$ with respect to the selling prices of the product in the competitive online channel.
$p_i$	Retailer price of product $i$
$p_{0i}$	The online price of product $i$
$w_i$	The wholesale price of manufacturer $i$
$t_i$	Carbon emission reduction rate of manufacturer $i$ (namely product greening level)
$\pi_{mi}$	The manufacturer's profit of supply chain $i$
$\pi_{ri}$	The retailer's profit of supply chain $i$
$rb_i$	Interest rate of return on bank loan for supply chain $i$

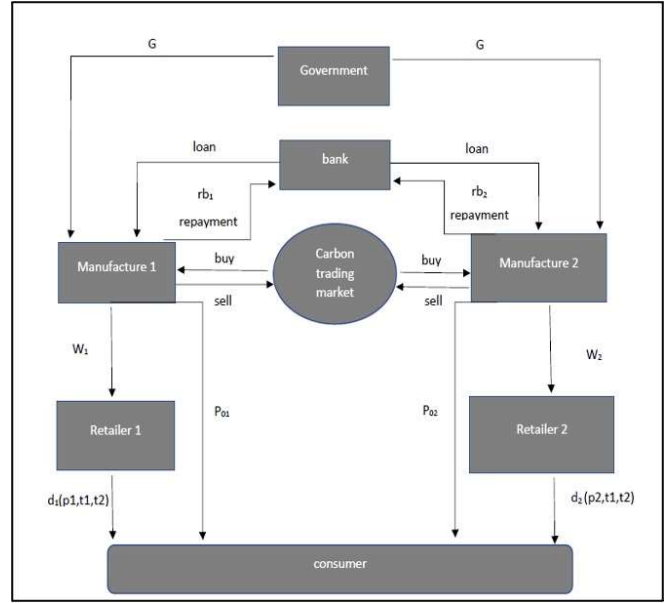


Figure 1. Supply chain structure

### A. Assumptions

- Carbon trading price is announced by the carbon trading market.
- There is a linear direction between total carbon emissions and production amount.
- Cost of carbon emissions reduction due to considering as investment cost does not have any impact on the unit of production cost.
- Transportation cost in online channel is marginal.
- Manufacturer's production cost is considered zero.
- The product demand is linear with the retail price product  $i$ , greening level of product  $i$  and greening level of product  $j$  and price of the rival supply chain through traditional channel and price of the product

in both online channels. The linear demand function can be expressed as follows:

$$d_{ir} = \alpha_i - \beta_i p_i + \gamma_i p_j + \gamma_{oi} p_{oi} + \gamma_{oj} p_{oj} + t_i - \lambda_j t_j \quad (1)$$

$$d_{io} = \alpha_{io} + \gamma_i p_i + \gamma_j p_j - \beta_{oi} p_{oi} + \gamma_{oj} p_{oj} + t_i - \lambda_j t_j \quad (2)$$

### III. MODEL AND ANALYTICAL RESULT

Two chains which are named supply chain 1 and supply chain 2 compete for attracting more Eco-friendly customers. In each supply chain, the manufacturer produces and sells low-carbon products to his retailer, and the retailer sells the products to consumers. The two chains compete on a greening level, which is determined by the manufacturer. In this section, some approaches, such as vertical and horizontal cooperation are discussed. The profits of the manufacturer, retailer, and supply chain are as follows, respectively.

$$\pi_{mi} = w_i d_{ir} + p_{oi} d_{oi} - k(e(1-t_i)d_i - G)(1+rb_i) - \frac{1}{2} m t_i^2 \quad (3)$$

$$\pi_{ri} = (p_i - w_i) d_{ir} \quad (4)$$

$$\pi_{sc} = p_i d_{ir} + p_{oi} d_{oi} - k(e(1-t_i)d_i - G)(1+rb_i) - \frac{1}{2} (m t_i^2) \quad (5)$$

#### A. Vertical Approach

In this approach, it is considered supply chain 1 and supply chain 2 are both decentralized (DD). Because of the nature of vertical structures, it is needed a model that can best fit the hierarchal perspective. Stackelberg has this feature where one of the members is powerful enough to dominate on the chain and takes the leader role and the follower will make his decision right after the optimal decision of his leader. A manufacturer-Stackelberg leader model is conducted as following which in the first stage manufacturers simultaneously and uncooperatively have to decide on their greening level, wholesale price, online price and in the second stage retailers decide on their retail price.

The upper level (leader):

$$\max_{(w_i, t_i, p_{oi}, rb_i)} \pi_m = \sum_{i=1}^2 w_i d_{ir} + p_{oi} d_{oi} - k(e(1-t_i)d_i - G)(1+rb_i) - \frac{1}{2} m t_i^2 \quad (6)$$

Subject to:

$$p_i - w_i \geq 0 \quad (7)$$

$$p_{oi} - w_i \geq 0 \quad (8)$$

$$0 \leq rb_i \leq 1 \quad (9)$$

$$0 \leq t_i \leq 1 \quad (10)$$

$$w_i \geq 0 \quad (11)$$

$$p_{oi} \geq 0 \quad (12)$$

Lower level (follower):

$$\max_{(p_i)} \pi_r = \sum_{i=1}^2 (p_i - w_i) d_{ir} \quad (13)$$

Subject to:

$$d_{ir} = \alpha_i - \beta_i p_i + \gamma_i p_j + \gamma_{oi} p_{oi} + \gamma_{oj} p_{oj} + t_i - \lambda_j t_j \quad (14)$$

$$d_{oi} = \alpha_{oi} + \gamma_i p_i + \gamma_j p_j - \beta_{oi} p_{oi} + \gamma_{oj} p_{oj} + t_i - \lambda_j t_j \quad (15)$$

$$p_i \geq 0 \quad (16)$$

Equation (6) maximize the total profit of manufacturers. Equation (7) and (8) denote that retail price and online price cannot be lower than the wholesale price. We can see the interest rate of return and carbon reduction rate are uniform between 0 and 1 in (9) and (10). Equation (11) and (12) keep Online price and wholesale price variables positive. Constraints in the lower level are conducted as follow: Equation (13) maximize the total profit of retailers. Equation (14) and (15) represent retailer demand and online demand of supply chain  $i$  functions that depend on some other variables such as retail price, online price, greening level of own supply chain and the rival. Equation (16) prevents the retail price from taking a negative amount.

#### B. Horizontal Cooperation Approach

In this approach, manufacturers are reluctant to have any cooperation with their retailers. They come to a union to maximize their total profit regardless of the retailer's profit. There are two decentralized supply chains that their manufacturers have cooperation with each other that is presented in (17).

$$\pi_m^H = \pi_{m1} + \pi_{m2} \quad (17)$$

The superscript H indicates the horizontal cooperation model.

For formulating this cooperation, a combination of exact method and meta-heuristic conducted in which the optimal solutions of retailers are as constraint of the manufacturers' model. To reach this, the derivation of retailers' profit function to  $p_1$  can be shown as:

$$\frac{\partial \pi_{r1}}{\partial p_1} = a_1 + t_1 - \beta_1 p_1 + \gamma_{o1} p_{o1} + \gamma_2 p_2 + \gamma_{o2} p_{o2} - \lambda_2 t_2 - \beta_1 (p_1 - w_1) = 0 \quad (18)$$

$$\frac{\partial \pi_{r2}}{\partial p_2} = a_2 + t_2 - \beta_2 p_2 + \gamma_{o1} p_{o1} + \gamma_1 p_1 + \gamma_{o2} p_{o2} - \lambda_1 t_1 - \beta_2 (p_2 - w_2) = 0 \quad (19)$$

By solving (18) and (19), optimal prices are:

$$p_1^* = \gamma_2 (a_2 + t_2 + \beta_2 w_2 + \gamma_{o1} p_{o1} + \gamma_{o2} p_{o2} - \lambda_1 t_1) + \beta_2 (2a_1 + 2t_1 + 2\beta_1 w_1 + 2\gamma_{o1} p_{o1} + 2\gamma_{o2} p_{o2} - 2\lambda_2 t_2) \quad (20)$$

$$p_2^* = \gamma_1 (a_1 + t_1 + \beta_1 w_1 + \gamma_{o1} p_{o1} + \gamma_{o2} p_{o2} - \lambda_2 t_2) + \beta_1 (2a_2 + 2t_2 + 2\beta_2 w_2 + 2\gamma_{o1} p_{o1} + 2\gamma_{o2} p_{o2} - 2\lambda_1 t_1) \quad (21)$$

By substituting we have:

$$p_1^* = \gamma_2 (A) + 2\beta_2 (D) \quad (22)$$

$$p_2^* = 2\gamma_1 (A) + \beta_1 (D) \quad (23)$$

The horizontal cooperation model is formulated as follow:

$$\max \pi_m^H = \sum_{i=1}^2 \pi_{mi} \quad (24)$$

Subject to:

$$p_1^* = \gamma_2 (A) + 2\beta_2 (D) \quad (25)$$

$$p_2^* = 2\gamma_1 (A) + \beta_1 (D) \quad (26)$$

$$p_i - w_i \geq 0 \quad (27)$$

$$p_{oi} - w_i \geq 0 \quad (28)$$

$$d_{ir} = \alpha_i - \beta_i p_i + \gamma_j p_j + \gamma_{oi} p_{oi} + \gamma_{oj} p_{oj} + t_i - \lambda_j t_j \quad (29)$$

$$d_{oi} = \alpha_{oi} + \gamma_i p_i + \gamma_j p_j - \beta_{oi} p_{oi} + \gamma_{oj} p_{oj} + t_i - \lambda_j t_j \quad (30)$$

$$0 \leq r b_i \leq 1 \quad (31)$$

$$0 \leq t_i \leq 1 \quad (32)$$

$$0 \leq w_i \quad (33)$$

$$0 \leq p_i \quad (34)$$

$$0 \leq p_{oi} \quad (35)$$

Sum of manufacturers' profit is maximized in (24). In (25) and (26) there are the optimal amount of retail prices. Equation (27) and (28) shows that online price and retail price should be more than wholesale price. It is considered retailer and online demand functions in (29) and (30), respectively. Equation (31) to (35) represent the upper and lower bound of decision variables.

### C. Solution Method

A bi-level programming for solving the model (I) and (II) is investigated. In this study, metaheuristic methods such as Bee algorithm (BA), Firefly algorithm (FA), Teaching learning-based algorithm (TLBA) and Imperialism algorithm (IA) is employed.

### D. Solution Representation

In vertical approach (model I), Follower model is considered as a limitation for the leader model. At first, the model of leader runs, and the optimal outputs will insert to the follower model as initial inputs. To solve these models, it is utilized a hybrid metaheuristic method to discover optimal solutions. By every iteration that runs with this method, the output of manufacturer's model includes wholesale price, carbon emission reduction rate, and the online price will transfer to retailer's model as inputs, then the output of the retailer problem which is the retail price will achieve. In the next step, variables will place in objective functions, and after all considered iteration implements on the model, the solution that maximizes the profit functions will be the answer to the problem. Two metaheuristic methods are implemented for this model. At first, the leader model is executed by Bee algorithm, and then the results take place in Firefly algorithm as inputs; this procedure will repeat until specific criterion meets.

There is not a hierarchal structure in the Horizontal approach (model II). Hence, we face a simple Stackelberg game in which manufacturers' strategy is to maximize their profit regardless of the retailer's profit. So, the optimal retail prices of retailers are known as constraints for the manufacturer's profit model. In other words, no bi-level approach is conducted to this model due to its structure.

The proposed individual representation of Bee for the model (I) and model (II) should be capable of generating a variety of solutions. The provided Bee includes five sections; the sections consider wholesale price, the online prices, interest rate of return, carbon emission reduction rate and the retail price which is a  $1 \times (w + p_0 + rb + t + p)$  string. The proposed chromosome for the model (II) has a little bit different from previous models. In this model, retail prices are a dependent variable which by obtaining other variables the value of retail

prices will achieve so we have a  $1 \times (w + p_0 + rb + t)$  string. The proposed Bee structure is illustrated in Figure 2. It is assumed two competitive supply chains; therefore, each gene consists of two parts. For instances, as it is observed in chromosome figure, the two parts of gene one represents the wholesale price of chain 1 and 2, respectively.

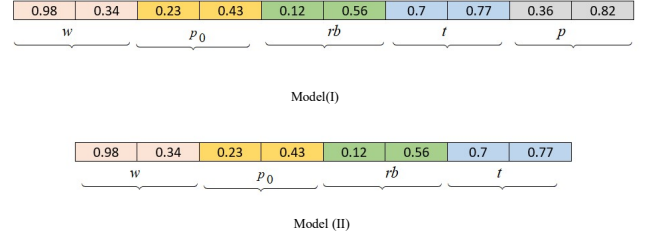


Figure 2. Individual representation of Bee

## IV. NUMERICAL EXAMPLE

To evaluate the performance of proposed algorithms, an example is defined and solved by all proposed algorithms. The parameter values of this example are shown in Table II. To fairly compare the performance of solution approaches, the defined example is run for five times. By averaging these five runs, the result for each algorithm is found.

Table II. Parameter values

Parameter	Value	Parameter	Value
$a_1$	100	$\gamma_2$	0.3
$a_2$	90	$\gamma_{01}$	0.2
$a_{01}$	80	$\gamma_{02}$	0.1
$a_{02}$	60	$\lambda_1$	0.2
$\beta_1$	0.8	$\lambda_2$	0.1
$\beta_2$	0.7	G	60
$\beta_{01}$	0.7	K	3
$\beta_{02}$	0.7	e	5
$\gamma_1$	0.2	m	1

As explained in the previous section, four metaheuristic algorithms (BA, FA, ICA, and TLBO) are applied to solve the presented mathematical models. Figures 2 and 3 show the convergence path of all applied algorithms for solving the models (I and II), respectively. As can be seen in this figure, the BA shows the weakest performance in improving the objective function. In model I, the performance of ICA is better than FA and TLBO, but in model II, these algorithms converge to the same value of the objective function. The obtained result is briefly reported in Table III. Comparison of proposed algorithms in terms of the CPU time is presented in Figure 4.

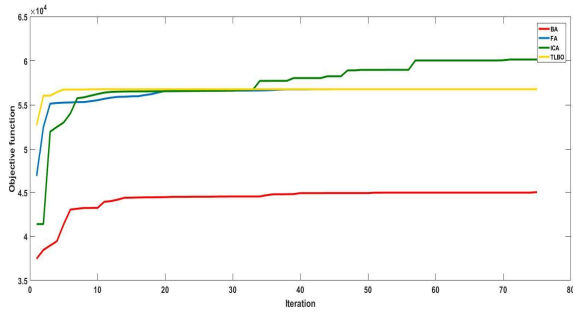


Fig. 2. The convergence path of all algorithms for solving the model I

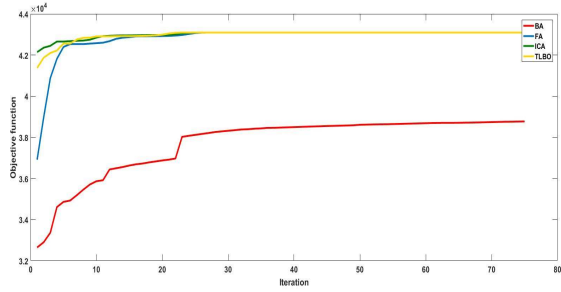


Figure 3. The convergence path of all algorithms for solving the model II

Table III. Computational results for model( I and II)

Algorithm	Model I		Model II	
	Revenue	CPU time (s)	Revenue	CPU time (s)
BA	44724.32	0.13	38801.06	0.69
FA	56768.41	2.85	43092.89	2.66
ICA	60437.75	0.28	43092.89	0.23
TLBO	56788.24	0.16	43092.89	0.11

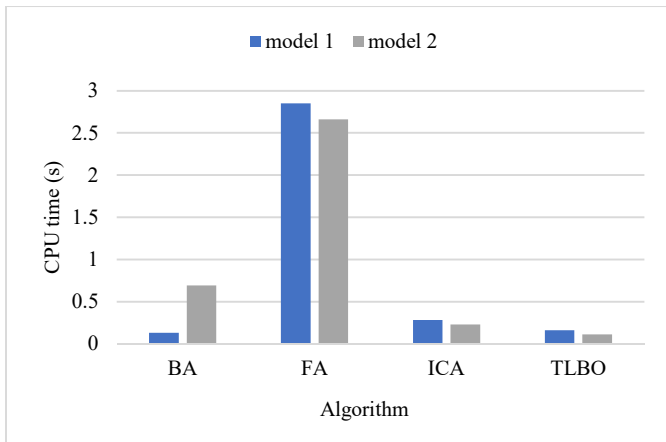


Figure 4. Comparison of proposed algorithms in terms of the CPU time for model 1 and 2

The comparison results of solving the models using hybrid meta-heuristic (III and IV) are slightly different compared with solving models (I and II). This is because of the solution

method of these models. Solving models ( III and IV ) need to use two solution approach. So, it is expected that the CPU time of solving these models greatly increase. The obtained result is shown in Table IV the convergence path of all applied algorithms for solving the models (III and IV) are shown in Figure 5 and 6, respectively. Figure 7 denotes the comparison result of the proposed algorithm for solving the model (III) and (IV) in terms of CPU time. The findings show that BA-TLBO has a better performance than BA-FA in finding a better solution.

Table IV. Computational results for model III and I

Algorithm	Model 3		Model 4	
	Revenue	CPU time (s)	Revenue	CPU time (s)
BA-FA	58665.28	183.17	46801.06	175.78
BA-TLBO	63539.01	221.87	47092.89	199.34

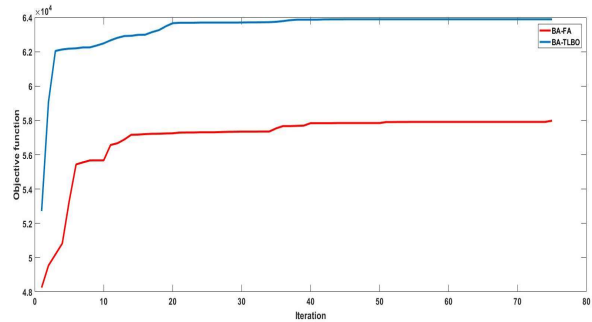


Figure 5. The convergence path of both algorithms for solving the model (III)

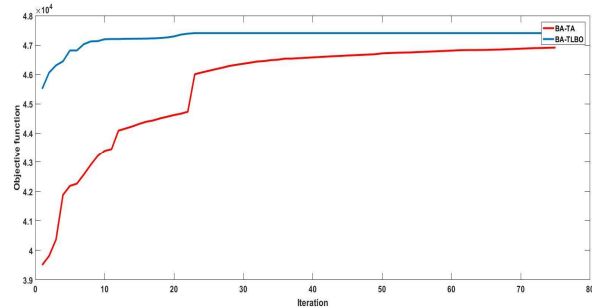


Figure 6. The convergence path of both algorithms for solving the model (IV)

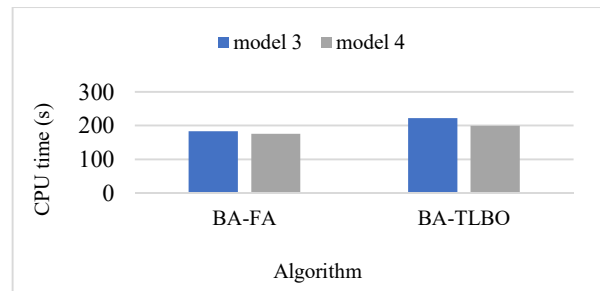


Figure 7. Comparison of proposed algorithms in terms of the CPU time for model (III and IV)

## V. CONCLUSION

In this paper, a Stackelberg game is implemented on vertical and horizontal approaches. In vertical approaches, leaders and followers try to maximize their profit simultaneously regardless of paying attention to the whole supply chain. In a horizontal approach, leaders willing to have better cooperation with each other though they want to maximize their profits. Metaheuristic and hybrid metaheuristic are employed to obtain optimal decision variables such as retailer prices, carbon emission reduction rate, bank interest rate, and wholesale price.

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