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Quantity-flexibility contract models for the supply chain with green-sensitive demand in the automotive manufacturing industry ^{*}

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Abstract. This paper considers a quantity-flexibility contract with green-sensitive demand in the automotive industry. The automobile manufacturer determines the green level, and the retailer determines the retail price. The authors apply game theory to build the models, optimize the green level for maximizing the automobile manufacturer's profit, and optimize the retail price for maximizing the retailer's profit. We consider the equilibrium decision between the green level and the retail price to maximize the supply chain's profit. Furthermore, we conduct experiments to verify our analysis results. Interestingly, this study finds that it is optimal for the retailer in the decentralized case to charge a higher price when the green sensitivity increases. However, the optimal price in the centralized case is not necessarily monotonic when the demand is lower. The manufacturer should set a higher green level as the greening investment parameter increases.

Keywords: Sustainable supply chain · quantity-flexibility contract · green-sensitive demand · game theory.

1 Introduction

In Paris, the government divides vehicles into six environmental classes. The air quality certificate increases customers' demand for green automobiles, including electric vehicles, natural gas vehicles, or hybrid vehicles. This phenomenon can reflect that more customers prefer buying environmentally-friendly automobiles and are sensitive to green products, which results in many automobile manufacturers and retailers begin to produce and sell green automobiles to meet customers' needs. Meanwhile, retailers require their automobile manufacturers

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to participate in carbon reduction disclosure projects, primarily from the necessary environmental certifications [10]. Therefore, facing the green-conscious consumer market, retailers cooperate with automobile manufacturers to initiate green product and process changes. This paper is motivated by this evidence and considers an automotive supply chain, including an automobile manufacturer and a retailer with green-sensitive customers' demand, and explores the influences of green-sensitive consumer demand on the supply chain members and the collaboration among them.

The greening improvement of green automobiles implies some attribute modifications, such as the use of electric or hydrogen-powered, and the combination of an internal combustion engine and an electric engine that reduces CO_2 emissions compared with the traditional gasoline or diesel automobiles [3]. After the air quality certificate starts working to raise the green level through green innovation, traditional automobile manufacturers need to invest in new technologies to produce plug-in hybrid automobiles as the green level improves. For example, producing 100% pure electric or hydrogen automobiles requires more managerial and technological investment to improve the green level. The automobile manufacturer may charge a green level and a higher unit cost than the condition where the order quantity is constant over time. The retailer must balance between the purchase, inventory holding, and shortage costs.

Automotive industries commonly use quantity-flexibility contracting as a necessary mechanism because the quantity-flexibility contract is a downstream protection contract, which can share the retailer's risk and increase the order quantities. Furthermore, the quantity-flexibility contract can coordinate the green supply chain of automotive manufacturing [14, 9, 8]. For example, Toyota Motor Corporation [6] currently uses the quantity-flexibility contract to deal with the variability in its production [12]. Although more practice about quantity-flexibility contracts appears in the automotive industries, few scholars research quantity-flexibility contracts in the green supply chain [4, 5, 13]. In this work, we propose the research question: How to optimize the green level and the retail price with green-sensitive demand to maximize the profits in the automotive industry?

To answer this question, we model a quantity-flexibility contract with green-sensitive demand between an automobile manufacturer and a retailer in the decentralized and centralized decision-making supply chain. Our work makes several contributions: First, this is one of the earliest researches to study quantity-flexibility contracts considering green-sensitive customers since a few previous studies have considered. Second, we combine quantity-flexibility contracts with green problems in the automobile industry because few types of research consider quantity-flexibility contracts in the automotive industry. Third, we find it optimal for the retailer in the decentralized case to charge a higher price when the green sensitivity increases. However, the optimal price in the centralized case is not necessarily monotonic when the demand is lower.

2 The model

We consider a practical problem between an automobile manufacturer and a retailer. The production plans of the assembly lines determine the demand for a component. However, the production plans may vary due to green-sensitive customer demand. The automobile manufacturer and retailer establish a quantity-flexibility contract in the green supply chain. Two key parameters of such a contract are nominal quantity Q and variation rate $\beta \in (0, 1)$, where $\beta = 0$ represents the inflexibility contract, and we also analyze this contract to validate the model, and Q is the quantity reserved by the retailer [11]. These parameters determine the interval $[Q(1 - \beta), Q(1 + \beta)]$ that the actual order quantities from the retailer must in [1]. When the order quantities are within this interval, the automobile manufacturer is committed to fulfilling them. The retailer commits herself to purchase, and the allowable range is determined as $[Q(1 - \beta), Q(1 + \beta)]$. According to Figure 1, we provide the sequence of events and decisions as follows: First, the automobile manufacturer offers the retailer a quantity-flexibility contract, and the retailer decides whether to accept it or not. Second, the retailer makes a nominal order quantity of green automobiles Q before the period starts if she accepts this contract. Then, she determines the retail price p . Third, the nominal order becomes the basis for the automobile manufacturer to determine his green level, and he needs to decide the green level θ . In automotive manufacturing, retailers intend to release orders as close as possible to the demand because of the limited storage space in the assembly plant and the high holding cost. On the other hand, demand variability prevents them from ordering a constant quantity in every period. The unit purchase cost is a linear or piecewise linear convex function for the quantity-flexibility contract. We give the expression of the automobile manufacturer's unit wholesale price $w(\beta) = c_0 + c_1\beta$, where c_0 represents the minimal possible cost with zero flexibility and c_1 is a fixed rate [2]. We consider that the supply chain players' green-sensitive demand x is a linear function of retail price p and green level θ , where θ is a continuous variable. The demand function is $x = a - bp + \alpha\theta$ [4], where $a > 0$ expresses the potential market size of green automobiles and $b > 0$ denotes the customer sensitiveness to the retail price of green automobiles, and $\alpha > 0$ represents customer's sensitivity to greening improvement level of green automobiles.

Referring to [4], we use an increasing and convex function to represent the cost incurred in improving the green level. The cost of greening is $I\theta^2$, where I indicates the greening investment parameter of green automobiles. For example, after the air quality certificate starts, traditional automobile manufacturers need to invest in new technologies to produce plug-in hybrid automobiles (Crit'Air 1 sticker) to raise the green level through green innovation. As a result, the initial green investment is relatively costly, and then raising the green level might be relatively inexpensive. When the green level improves, more managerial and technological investment is required for further improvement in the green level, making it more expensive to reach the goal of a higher green level comparable with that at the early stage. To avoid trivial cases, let $I > \theta^2 - 4b$. In the view

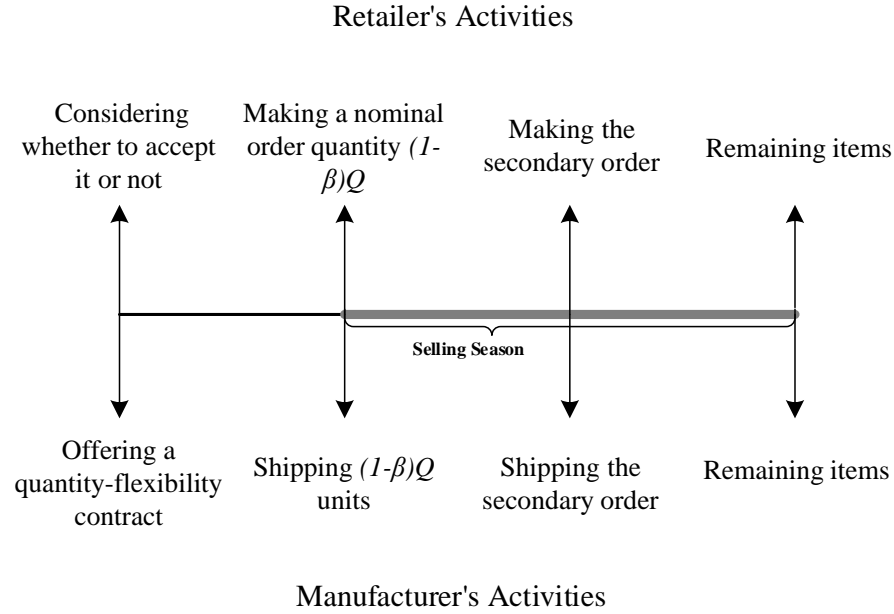


Fig. 1. Sequence of events under a quantity-flexibility contract

of consumers' sensitivity to greening and price, green innovation requires higher investment, consistent with the actual situation of product innovation [4]. The automobile manufacturer bears the cost of greening.

2.1 Decentralized decision-making policy

In the decentralized decision-making supply chain, the automobile manufacturer chooses the product green level θ for his profit maximization using the retailer's response function. Then, the retailer decides the retail price p to maximize her profit given the green level.

If the demand of green-sensitive customers is less than $Q(1 - \beta)$, the retailer buys at the minimum commitment $Q(1 - \beta)$, and thus, the automobile manufacturer sells to the retailer. If the demand of green-sensitive customers is in the interval $[Q(1 - \beta), Q(1 + \beta)]$, the retailer buys green automobiles in quantity to the demand of affected areas. If the demand of green-sensitive customers is greater than $Q(1 + \beta)$, the retailer buys at maximum the automobile manufacturer's commitment level and will have $x - Q(1 + \beta)$ product shortage to satisfy. As $x = a - bp + \alpha\theta$, $b > 0$, and $p > 0$, we can get $x < a + \alpha\theta$. We give the order quantity in Equation (1) by following the principle of quantity-flexibility

contract.

$$q = \begin{cases} Q(1 - \beta), & 0 \leq x < Q(1 - \beta), \\ x, & Q(1 - \beta) \leq x \leq Q(1 + \beta), \\ Q(1 + \beta), & Q(1 + \beta) < x < a + \alpha\theta. \end{cases} \quad (1)$$

According to Equation (1), we can get the profit of the automobile manufacturer as follows:

$$\pi_M(\theta) = \begin{cases} wQ(1 - \beta) - (h_M + c_f + c_t + c_m + c_l)Q(1 + \beta) - I\theta^2, & 0 \leq x < Q(1 - \beta), \\ wx - (h_M + c_f + c_t + c_m + c_l)Q(1 + \beta) - I\theta^2, & Q(1 - \beta) \leq x \leq Q(1 + \beta), \\ wQ(1 + \beta) - (h_M + c_f + c_t + c_m + c_l)Q(1 + \beta) - I\theta^2, & Q(1 + \beta) < x < a + \alpha\theta. \end{cases} \quad (2)$$

The first term of Equation (2) is derived from demand satisfaction and the second term represents manufacturing and inventory costs for the automobile manufacturer, and the last term specifies the green cost of the automobile manufacturer. Then, the profit function of the retailer is:

$$\pi_R(p) = \begin{cases} px - wQ(1 - \beta) - h_R[Q(1 - \beta) - x], & 0 \leq x < Q(1 - \beta), \\ px - wx, & Q(1 - \beta) \leq x \leq Q(1 + \beta), \\ pQ(1 + \beta) - wQ(1 + \beta) - s[x - Q(1 + \beta)], & Q(1 + \beta) < x < a + \alpha\theta. \end{cases} \quad (3)$$

Similar to Equation (2), the first term of the function is derived from demand satisfaction and the second term represents the retailer's purchasing cost, and the last term specifies the retailer's inventory or shortage cost.

First, the retailer determines the optimal retail price, and we can derive the following proposition:

Proposition 1. *If the demand is less than $Q(1 - \beta)$, the retailer's profit function is concave with p , and the optimal p^* is $p = \frac{a + \alpha\theta - h_R b}{2b}$. If $Q(1 - \beta) \leq x \leq Q(1 + \beta)$, the retailer's profit function is concave with p and the optimal $p^* = \frac{a + \alpha\theta + (c_0 + c_1\beta)b}{2b}$. If the demand is more than $Q(1 + \beta)$, the retailer's profit is increasing in p and the optimal $p^* = \frac{a + \alpha\theta - Q(1 + \beta)}{b}$.*

From Proposition 1, we find that when green-sensitive demand is less than $Q(1 - \beta)$, the retailer must purchase $Q(1 - \beta)$, which results in holding $Q(1 - \beta) - x$ inventory. The profit is affected by the retail price, the green level, and unit inventory holding cost. So, we get the optimal $p^*(\theta) = \frac{a + \alpha\theta - h_R b}{2b}$. When green-sensitive demand is in the interval $[Q(1 - \beta), Q(1 + \beta)]$, the retailer can purchase automobiles to satisfy all demand without inventory holding cost. The profit is affected by the retail price, the green level, and the automobile manufacturer's wholesale price (the variation rate). So, we get the optimal $p^*(\theta) = \frac{a + \alpha\theta + (c_0 + c_1\beta)b}{2b}$. When green-sensitive demand is more than $Q(1 + \beta)$, since the maximum order quantity is $Q(1 + \beta)$, the retailer's profit is increasing in p . However, the retail price is limited by the green level and the variation rate and the optimal $p^*(\theta) = \frac{a + \alpha\theta - Q(1 + \beta)}{b}$.

Then, the retailer decides the retail price in line with Proposition 1. After getting this response, the automobile manufacturer optimizes his own profit and determines the optimal green level, as shown in the following proposition:

Proposition 2. *If the demand of green-sensitive customer $0 \leq x < Q(1 - \beta)$ or $Q(1 + \beta) < x < a + \alpha\theta$, the automobile manufacturer's profit function is decreasing in θ . If the demand is less than $Q(1 - \beta)$, the optimal $\theta^* = 0$. If the demand is more than $Q(1 + \beta)$, the optimal $\theta^* = \frac{Q(1+\beta)-a+b\beta}{\alpha}$. If $Q(1 - \beta) \leq x \leq Q(1 + \beta)$, the profit function of the automobile manufacturer with θ is concave. The optimal θ is $\theta^* = \frac{\alpha(c_0+c_1\beta)}{2I}$ and the optimal retail price is $\frac{2Ia+(c_0+c_1\beta)(\alpha^2+2Ib)}{4Ib}$.*

From Proposition 2, we know that when green-sensitive demand is less than $Q(1 - \beta)$ or more than $Q(1 + \beta)$, no need appears for the automobile manufacturer to increase the green level. Because when green-sensitive demand is less than $Q(1 - \beta)$, customers are less sensitive to green automobiles, which increases that the green level will not attract more customers to purchase green automobiles and eventually leads to lower profits. When green-sensitive demand is more than $Q(1 + \beta)$, customers are more sensitive to green automobiles. However, due to the maximum order quantity is $Q(1 + \beta)$, the increase of the green level will not improve the profit but will increase the green investment cost. When green-sensitive demand is in the interval $[Q(1 - \beta), Q(1 + \beta)]$, the automobile manufacturer's profit will first increase and then decrease as the green level increases, and we get the optimal green level $\theta^* = \frac{\alpha(c_0+c_1\beta)}{2I}$.

2.2 Centralized decision-making policy

In this centralized decision-making policy, we consider the automobile manufacturer and the retailer as a whole to maximize the channel profit by choosing the green level and the retail price. Thus, the profit function of the supply chain is as follows,

$$\pi_{SC}(\theta, p) = \begin{cases} px - (h_M + c_f + c_t + c_m + c_i)Q(1 + \beta) - h_R[Q(1 - \beta) - x] - I\theta^2, & 0 \leq x < Q(1 - \beta), \\ px - (h_M + c_f + c_t + c_m + c_i)Q(1 + \beta) - I\theta^2, & Q(1 - \beta) \leq x \leq Q(1 + \beta), \\ pQ(1 + \beta) - (h_M + c_f + c_t + c_m + c_i)Q(1 + \beta) - s[x - Q(1 + \beta)] - I\theta^2, & Q(1 + \beta) < x < a + \alpha\theta. \end{cases} \quad (4)$$

In the centralized decision-making supply chain, we solve the supply chain's profit function and get the following proposition:

Proposition 3. *If the demand of greens-sensitive customer is less than $Q(1 - \beta)$, the supply chain's profit function is jointly concave in θ and p , and the optimal $\theta^* = \frac{\alpha\alpha}{4Ib-\alpha^2}$ and $p^* = \frac{2Ia-h_R\alpha^2-2Ih_Rb}{4Ib-\alpha^2}$. If the demand of green-sensitive customer is in $[Q(1 - \beta), Q(1 + \beta)]$, the supply chain's profit function is jointly concave in θ and p , and the optimal $\theta^* = \frac{\alpha\alpha}{4Ib-\alpha^2}$ and $p^* = \frac{2Ia}{4Ib-\alpha^2}$.*

From Proposition 3, we find that when green-sensitive demand is less than $Q(1 - \beta)$, customers are less sensitive to green automobiles, the retailer must purchase $Q(1 - \beta)$, which results in holding $Q(1 - \beta) - x$ inventory. The profit of the supply chain is affected by the retail price, the green level, and unit inventory holding cost. So, we get equilibrium values for the supply chain. The optimal $\theta^* = \frac{a\alpha}{4Ib - \alpha^2}$ and $p^* = \frac{2Ia - h_R\alpha^2 - 2Ih_Rb}{4Ib - \alpha^2}$. When green-sensitive demand is in the interval $[Q(1 - \beta), Q(1 + \beta)]$, the retailer can purchase automobiles to satisfy all demand without inventory holding cost. The profit is affected by the retail price, the green level, and the automobile manufacturer's wholesale price (the variation rate). The optimal $\theta^* = \frac{a\alpha}{4Ib - \alpha^2}$ and $p^* = \frac{2Ia}{4Ib - \alpha^2}$. When green-sensitive demand is more than $Q(1 + \beta)$, the supply chain's profit function is decreasing in θ and increasing in p , and equilibrium values do not exist.

2.3 Equilibrium analysis

In this subsection, we analyze the equilibrium strategies derived by Propositions 2 and 3, and find the condition that the optimal solutions can sustain. The primary purpose is to solve the coordination problem of the members in the supply chain. First, we can obtain the condition that the equilibrium strategies exist according to the demand function because the quantity in the centralized case must be not less than that in the decentralized case based on the principle of the members' coordination. Since the optimal quantity in the range of $Q(1 - \beta) \leq x \leq Q(1 + \beta)$ under the decentralized decision-making policy is $q^* = \frac{2abI}{4bI - \alpha^2}$. By comparing the optimal quantities in the decentralized case and that in the centralized case, we can obtain the following proposition:

Proposition 4. *When $c_0 + c_1\beta \geq \frac{2a\alpha^2I}{-\alpha^4 - 8b^2I^2 + 6\alpha^2bI}$, the supply chain coordination can be sustained in the range of $x \in [Q(1 - \beta), Q(1 + \beta)]$, otherwise, the optimal solutions may not exist.*

Then, we analyze the equilibrium strategies in the decentralized case. By computing these equilibrium solutions in Proposition 2, we can examine the impact of α , c , and I on the performance measures associated with different members and obtain the following proposition:

Proposition 5. *As α or β increases, the optimal price p^* or the optimal green level θ^* also increases, i.e., $\frac{dp^*}{d\alpha} \geq 0$ and $\frac{d\theta^*}{d\beta} \geq 0$. Moreover, when c_0 or c_1 increases, the optimal green level θ^* increases, i.e., $\frac{d\theta^*}{dc_0} \geq 0$ and $\frac{d\theta^*}{dc_1} \geq 0$. When I increases, the optimal green level θ^* decreases, i.e., $\frac{d\theta^*}{dI} \leq 0$.*

For $\frac{dp^*}{d\alpha} \geq 0$ in Proposition 5, we find that both p^* and θ^* are increasing in α . The reason is that consumers are more sensitive to the green level in the automobile manufacturer with the increases of α , which indicates that they are willing to pay more for a higher greening improvement level and the manufacturer can set a higher price. For $\frac{d\theta^*}{dc_0} \geq 0$ and $\frac{d\theta^*}{dc_1} \geq 0$, we can explain them as follows: The optimal green level θ^* will be affected by the minimal possible cost with zero flexibility and the minimal possible cost with the fixed rate because

the wholesale price includes them. Thus, the increased wholesale price means more investment and efforts for green automobiles, which improves the green level. The reason for $\frac{dp^*}{d\beta} \geq 0$ is similar to some explanations for $\frac{d\theta^*}{dc_0} \geq 0$ and $\frac{d\theta^*}{dc_1} \geq 0$ because the wholesale price is also increasing in β . Interestingly, from Proposition 5, we can find that $\frac{d\theta^*}{dI} \leq 0$ represents that the manufacturer who has a lower marginal cost for any given quality in the quantity-flexibility contract is an inefficient firm [7].

Now, we turn to the equilibrium solutions in the centralized case. We can establish the following monotonicity results for the centralized decision-making policy after computing the optimal solutions in Proposition 3:

Proposition 6. *Under the centralized case, the optimal solutions exhibit the following characteristics:*

- (i) *If the demand is less than $Q(1 - \beta)$, the optimal price p^* is nonmonotonic in α or b , i.e., $\frac{dp^*}{d\alpha} \leq 0$ when $a \in (0, 3bh_R)$ and $\frac{dp^*}{d\alpha} \geq 0$ when $a \geq 3bh_R$; $\frac{dp^*}{db} \leq 0$ when $a \geq \frac{3\alpha^2 h_R}{4I}$ and $\frac{dp^*}{db} \geq 0$ when $a \in (0, \frac{3\alpha^2 h_R}{4I})$. As I increases, the optimal green level θ^* decreases, i.e., $\frac{d\theta^*}{dI} \leq 0$.*
- (ii) *Unlike $x < Q(1 - \beta)$, the optimal price p^* is increasing in α and decreasing in b if the demand is in the range of $[Q(1 - \beta), Q(1 + \beta)]$, i.e., $\frac{dp^*}{d\alpha} \geq 0$ and $\frac{dp^*}{db} \leq 0$.*

From Proposition 6 (i), we can find that the optimal price p^* could first decrease and then increase in α given $a > 0$. This is because when the market potential is smaller, fewer consumers are concerned about EVs, which causes the retailer to lower the price to attract customers to buy. When the market potential is larger, more consumers are starting to pay attention to greenness. Thus, the retailer can raise the price to obtain more profits. The same explanation also applies to $\frac{dp^*}{db}$ and we also find that the optimal price p^* first increases and then decreases in b . The reason is that when the retailer is indifferent about the price-sensitivity of consumer when the market potential is smaller. When the market potential is larger, the retailer may lower the price because customers' higher price sensitivity means the higher demand reduction. Interestingly, Proposition 6 (ii) tells us that if $x \in [Q(1 - \beta), Q(1 + \beta)]$, the monotonicity of parameters α and b is different from that in $x < Q(1 - \beta)$. An important reason is that as the retailer's order quantity increases, the demand in the market also increases, which influences the market potential that is larger than $3bh_R$ or $\frac{3\alpha^2 h_R}{4I}$. So, the monotonicity of α and b has changed.

3 Concluding remarks

This paper studies a quantity-flexibility contract between a manufacturer and a retailer with green-sensitive demand in the automotive industry. In a decentralized supply chain, we use game theory to solve the problem. The automobile

manufacturer acts as the Stackelberg leader to set the green level, and the retailer acts as the follower to set the retail price. We determine the optimal green level to maximize the automobile manufacturer's profit and the retail price to maximize the retailer's profit. Under centralized decision-making, we consider the equilibrium decision between the automobile manufacturer and the retailer. We use the game theory to analyze the model to maximize the supply chain's profit. We analyze the equilibrium strategies and find the condition that the optimal solutions can sustain. This paper is one of the first researches to study quantity-flexibility contract considering green-sensitive customers. We propose a novel collaboration model in quantity-flexibility contract considering green issues. It is optimal for the retailer in the decentralized case to charge a higher price when green-sensitivity increases; however, the optimal price in the centralized case is not necessarily monotonic when the market potential is low. Interestingly, we also find that the supply chain with the quantity-flexibility contract does not always generate more profits than its inflexibility counterpart; it mainly depends on the retail price and greenness improvement level. Our results can be applied to maximize the profits on both upstream and downstream partners with quantity-flexibility contracts in the green supply chain.

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