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Game Theoretic Analysis of Exclusive Contract for Carbon Fiber Reinforced Plastic in the Aviation Industry

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Abstract

We investigate the rationality of an exclusive supply contract for Carbon Fiber Reinforced Plastic (CFRP) between one of the two largest aircraft manufacturers in the world, Boeing, and a Japanese CFRP supplier, Toray. It appears irrational that in 2004 Boeing dared to choose Toray as the sole CFRP supplier for their new B787 aircraft, and exclude other CFRP suppliers for the next 18 years, instead of letting several suppliers compete on price. On the basis of game theory, we build a mathematical model of the market for CFRP comprising Toray and the oligopolistic market for aircraft, assuming the other huge aircraft manufacturer, Airbus, as Boeing's rival. Consequently, we derive subgame perfect Nash equilibria using backward induction and observe its outcome. The results show that under specific conditions, such a contract can be a rational strategy by both companies, Boeing and Toray. In the model, an aircraft is defined as a product consisting of two materials, CFRP and aluminum. Two decision stages about production by Boeing and Airbus are done sequentially. In each stage, the amount of CFRP is first determined by the market and then the manufacturer determines the amount of aluminum. However, in advance of this stage Toray has been given a chance to propose the amount of CFRP for the case of exclusive supply. In order to be chosen as the exclusive supplier, Toray should propose the total amount of CFRP which are produced by both suppliers in the Cournot competitive market. It implies that Toray has an incentive to discount the price of CFRP from desirable price for purely monopolized market. Thus, designating a supplier as the exclusive one is rational action for manufacturers because it creates the possibility to make the price of material lower.

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Keywords: Carbon fiber; Aviation industry; Exclusive contract; Game theory; Cournot competition

1. Introduction

Carbon fiber, produced from heat-treated organic carbon, is usually epoxy coated and then baked to make a complex material called Carbon Fiber Reinforced Plastic (CFRP). CFRP is lightweight and has high mechanical strength in one-tenth the volume of steel; i.e., it has the same strength has steel but less weight. In addition, because it is not metal, it does not corrode, has various means for chemical resistance, and is easy to maintain. Further, when burned, it can easily change its nature by combining with various kinds of plastic.

These properties are invaluable for the aviation industry in the production of aircraft. Consequently, it has been utilized since the 1970s—at first only for a part of the tail unit in Boeing B737s and B767s. Subsequently, in the 1990s, it was additionally utilized in the main wing.

In the 2000s, Boeing and Airbus began to utilize CFRP for virtually the entire body of their aircraft and competed to develop new aircraft using CFRP; ultimately resulting in Boing's B787 and Airbus' A350XWB flagship mid-range 200–300-seater aircraft being predominantly composed of CFRP. Because these aircraft expend less fuel than previous models, they are able to fly as long as larger aircraft. These changes made it possible to extend the line from Asia to Europe and America, where the flight time was previously considered too long to be profitable. Consequently, CFRP is now the main material for aircrafts.

The Japanese producers of CFRP, Toray, Toho Tenax, and Mitsubishi Rayon, occupy 70% of the total world market and are therefore the main players. The turning point came in 2006 when Boeing signed the exclusive contract to source CFRP only from Toray. After 18 years, Toray has become a monopoly provider of CFRP to Boeing. Usually, in a monopoly situation,

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prices are higher than in a competitive situation with rivals. In addition, there is a high risk of the supply of material becoming limited. Thus, the exclusive contract appeared to be a bad deal for Boeing.

Airbus' strategy is opposite to that of Boeing. It procured the CFRP for A350XWB from four CFRP suppliers: Hexel and Cytec in the US, and Toray and Toho Tenax in Japan. Thus, Toray was only one of their suppliers.

Hax [1] proposed a customer relationship-focused company strategy called delta mode. The model propounds "system lock-in," in which firms impound customers and exclude rivals from the market to obtain the position of leader and competitive superiority in that market. Okamura [2] reported that Boeing's exclusive contract with Toray is an application of that system lock-in principle. Because Toray's CFRP is exclusively used by Boeing, Toray can attain the position of trusted brand and become the leader in the CFRP market. Additionally, Toray receives merit for cost reduction from expanding production and enhancing the quality of specialized aircrafts.

The exact details of the contract signed between Boeing and Toray are confidential, and hence unknown by us. Therefore, we focus on the monetary incentive for both parties to sign this exclusive contract. That is, our goal is to mathematically analyze the rationality of the exclusive contract of Boeing with Toray from the aspect of monetary profits, i.e., economic incentive. We utilize game theory, which mathematically analyzes a firm's strategy which maximize its profits considering rival's strategy and profits.

The remainder of this article is organized as follows. Section 2 describes the model used in our analysis. Section 3 analyzes the optimal solution in the subgame perfect Nash equilibrium. Section 4 concludes this paper.

2. Model description and notations

2.1. Game construction

For this model, we assume that two firms—Toray and its rival—provide the same quality CFPR. Further, there are two aircraft firms: Boeing and Airbus. The respective number of aircrafts produced by Boeing and Airbus is defined as Q_B, Q_A, respectively. The new types of aircraft are almost all produced from aluminium and CFRP. Therefore, this study assumes the production function of an aircraft, Q_i, is a combination of CFRP K_i, and aluminium A_i.

$$Q_i = a\{\alpha K_i + (1-\alpha)A_i\}, \alpha > \frac{1}{2} \tag{1}$$

where a is the proportionality coefficient and α is the technological coefficient. Because CFRP comprises more than half of all materials in the new aircraft, we set α as shown above. The price of an aircraft is determined to be that of market price, which is defined as the reduction function of total quantity produced by the firms. This total quantity is defined as $Q = Q_B + Q_A$. We define the highest price as P_0 if there is no supply, $Q = 0$. Then, the market price is determined as

$$P(Q) = P_0 - Q \text{ if } Q < P_0 \tag{2}$$
$$P(Q) = 0, \text{otherwise} \tag{3}$$

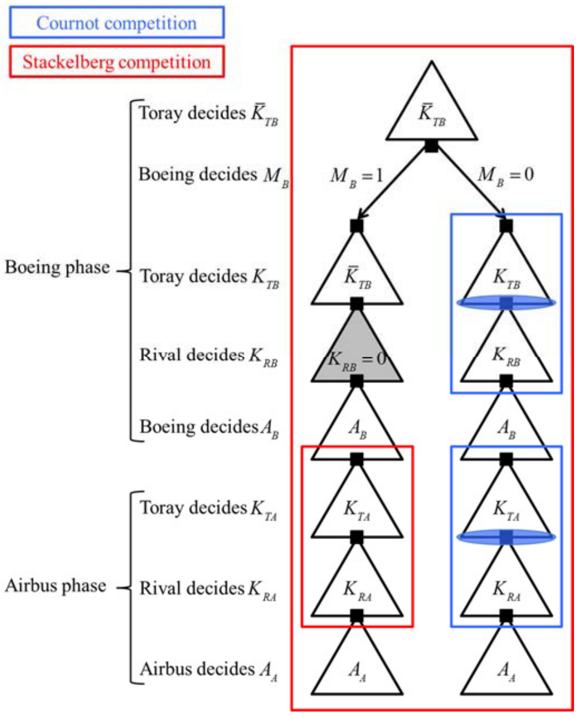

Fig. 1. Decision-making game tree.

In this game, we consider the sequential game stages shown in Fig. 1.

First sequence: Boeing phase

- Stage 1: Toray decides whether to offer a monopolized contract to Boeing.
- Stage 2: Boeing either accepts or rejects the offer. If it is rejected, Toray needs to compete with its rivals to sell CFRP.
- Stage 3: Toray decides how many units of CFRP to provide to Boeing.
- Stage 4: The rival firm decides how many units of CFRP to provide to Boeing.
- Stage 5: Boeing decides how many units of aluminium to use.

Second sequence: Airbus phase

- Stage 6: Toray decides how many units of CFRP to provide to Airbus.
- Stage 7: The rival firm decides how many units of CFRP to provide to Airbus.
- Stage 8: Airbus decides how many units of aluminium to use.

Boeing's 787 action plan started from 2002, which is earlier than that of Airbus' A350XWB in 2006. To build this history into the model for the competition between aircraft manufacturers, Boeing first decides Q_B and then Airbus decides Q_A. This game is a kind of Stackelberg game between

Boeing and Airbus from the aspect of aircraft production. The CFRP is rare material for aircraft manufacturers so that Toray can offer to Boeing. It is also a Stackelberg game between Toray and Boeing from the aspect of CFRP production.

2.2 Boeing phase

In the Boeing phase, the price of CFRP, p, is reduction function of production of CFRP described as below

$$P(K_B) = p_0 - K_B \tag{4}$$

We define the highest price as p_0 if there is no supply, $K = 0$. The amount of CFRP from Toray to Boeing is K_{TB}, and that from the rival is K_{RB}. Thus, the total amount of CFRP for Boeing is $K_B = K_{TB} + K_{RB}$. Each firm incurs the following cost, C, for producing CFRP:

$$C(K_{iB}) = cK_{iB}, i \in \{T, B\} \tag{5}$$

There is no fixed cost and the marginal cost is constant, c.

In the Boeing phase, the CFRP suppliers obtain the following profits:

$$\pi_{iB} = (p_0 - K_B)K_{iB} - cK_{iB} \tag{6}$$

The total cost for Boeing to use CFRP is

$$C(K_B) = (p_0 - K_B)K_B \tag{7}$$

The cost to Boeing of using aluminium A_B is

$$C(A_B) = wA_B \tag{8}$$

That is, there is no fixed cost and the marginal cost w is constant. Then, the profits obtained by Boeing are as follows:

$$\pi_B = (P_0 - Q_B - Q_A)Q_B - (p_0 - K_B)K_B - wA_B \tag{9}$$

In the Boeing phase, at the first node before Boeing makes its decision, Toray has a chance to offer an exclusive contract to Boeing. The amount of CFRP Toray provides to Boeing is, $\overline{K}_{TB}$ which is predetermined in the contract.

Boeing has a chance to accept this offer or reject it to obtain the CFRP from the competing market. The decision-making by Toray at this stage is represented as M_B. If the offer is accepted, $M_B = 1$, Toray necessarily provides $\overline{K}_{TB}$ and Boeing does not buy any CFRP from the rival so that $K_{RB} = 0$. Otherwise, following pre-described steps, Toray needs to compete with its rival in the market to provide it to the aircraft firms. In this case, Toray and the rival decide on the amounts of CFRP simultaneously. This is called a Cournot quantity competition game. This model is represented as a situation in which no leading company exists and only a few providers compete with each other in a new market.

2.3 Airbus phase

The cost and profit functions for Airbus are exactly the same as those for Boeing. In the Airbus phase, we define the CFRP produced by Toray and the rival, K_{TA} and K_{RA}, respectively. The price of CFRP is defined as

$$P(K_A) = p_0 - K_A \tag{10}$$

The cost of producing CFRP for the CFPR firm to Airbus is defined as

$$C(K_{iA}) = cK_{iA}, i \in \{T, B\} \tag{11}$$

This is the same as that to Boeing.

Note that there are two situations in this phase—respectively associated with acceptance or rejection of Toray's offer.

First, if Boeing accepts the offer, Toray becomes the market leader and this market becomes a Stackelberg competition. This model setting is represented as a situation in which Boeing signs the contract, and Toray joins the Boeing 787 action plan monopoly and obtains the know-how to be the leader in the CFRP market in the Airbus phase.

On the other hand, if Boeing rejects it, Toray cannot become the leader and they compete as in the same situation, which is the Cournot competition. As a result of competition in the Boeing phase, both firms obtain the same level of know-how simultaneously and there is no leader in this phase. Thus, each firm obtains the profits below:

$$\pi_{iA} = (p_0 - K_A)K_{iA} - cK_{iA} \tag{12}$$

The cost to Airbus of using CFRP, K_A is

$$C(K_A) = (p_0 - K_A)K_A \tag{13}$$

The cost for using aluminium A_A is the same as that for Boeing:

$$C(A_A) = wK_A \tag{14}$$

, where w is the marginal cost function and it is constant.
Thus, the profit obtained by Airbus is given by.

$$\pi_A = (P_0 - Q_B - Q_A)Q_A - (p_0 - K_A)K_A - wA_A \tag{15}$$

Throughout these two phases, the total profit obtained by each CFRP firm is a summation of the profit in each phase:

$$\pi_i = \pi_{iB} + \pi_{iA} \tag{16}$$

2.3. Subgame perfect Nash equilibrium

The Nash equilibrium is defined as follows:

Definition: *A strategy profile is a Nash equilibrium if the profits induced from that strategy are not less than that from another strategy for every player.*

On the basis of this definition, the subgame perfect Nash equilibrium is defined as follows:

Definition: *A strategy profile is a subgame perfect Nash equilibrium if it becomes a Nash equilibrium in any subgame (stage).*

To analyze the subgame perfect Nash equilibrium, we analyze the firms' behaviors in backward. In other words, we first analyze their behavior in the Airbus phase and then in the Boeing phase. In each phase, we first consider aircraft manufacturer and then move on to the CFRP suppliers.

3. Analysis

3.1. Exclusive contract case

By using backward induction, we first solve the Nash equilibrium in the Airbus phase for the case where the exclusive contract is signed. First we solve optimal (K_B, A_B, K_A) to maximize the profits for Airbus π_A.

$$\max\ \pi_A = -a^2(1-\alpha)^2 A_A^2 - a^2(1-\alpha)\alpha K_A A_A + a(P_0 - Q_B - a\alpha K)(1-\alpha)A_A + a(P_0 - Q_B - a\alpha K_A)\mathrm{a}K_A - (p_0 - K_A)K_A - wA_A \quad (17)$$

Solving $\frac{\partial \pi_A}{\partial A_A} = 0$, the best response function for Airbus to K_B, A_B, K_A is

$$R(A_A) = \frac{1}{2a(1-\alpha)}\left\{-2a\alpha K_A + P_0 - Q_B - \frac{1}{a(1-\alpha)}w\right\} \quad (18)$$

Next, we solve the optimal solution of CFRP for Toray and the rival to maximize their profits. In this case, Toray can be the leader in the market because it obtains know-how as a result of the exclusive contract in the Boeing phase. Therefore, we solve the Stackelberg Nash equilibrium in this game.
First we solve the optimal quantity of CFRP, K_{RA}, the rival maximize its profits, given Toray's strategy K_{TA}.

$$\max \pi_{RA} = -K_{RA}^2 + (p_0 - K_{TA} - c)K_{RA} \quad (19)$$

Solving $\frac{\partial \pi_{RA}}{\partial K_{RA}} = 0$, the best response function for the rival to Toray is

$$R(K_{RA}) = \frac{1}{2}(p_0 - K_{TA} - c) \quad (20)$$

To maximize Toray's profit after considering this best response function.

$$\max\ \pi_{TA} = \frac{1}{2}(p_0 - K_{TA} - c)K_{TA} \quad (21)$$

Solving $\frac{\partial \pi_{TA}}{\partial K_{TA}} = 0$, the optimal solution for Toray is

$$K_{TA}^* = \frac{1}{2}(p_0 - c) \quad (22)$$

Applying the solution above, we obtain the solution for the rival,

$$K_{RA}^* = \frac{1}{4}(p_0 - c) \quad (23)$$

Then,

$$K_A^* = \frac{3}{4}(p_0 - c) \quad (24)$$

Thus, Toray and the rival obtain the following profits:

$$\pi_{TA} = \frac{1}{8}(p_0 - c)^2 \quad (25)$$

$$\pi_{RA} = \frac{1}{16}(p_0 - c)^2 \quad (26)$$

Therefore, we obtain the best response function as

$$R(Q_A) = \frac{1}{2}\left\{P_0 - Q_B - \frac{1}{a(1-\alpha)}w\right\} \quad (27)$$

Next, we consider Boeing phase to solve A_B to maximize π_B, given K_B and $R(Q_A)$:

$$\max\ \pi_B = -\frac{1}{2}a^2(1-\alpha)^2 A_B^2 + \{-a^2(1-\alpha)\alpha K_B + \frac{1}{2}a(1-\alpha)P_0 - \frac{1}{2}w\}A_B + \frac{1}{2}a\alpha\{P_0 - a\alpha K_B + \frac{1}{a(1-\alpha)}w\}K_B - (p_0 - K_B)K_B \quad (28)$$

Solving $\frac{\partial \pi_B}{\partial A_B} = 0$, we obtain the best response function for Boeing using aluminium to the CFRP from Toray and the rival.

$$R(A_B) = -\frac{\alpha}{1-\alpha}K_B + \frac{1}{2a(1-\alpha)}P_0 - \frac{1}{2a^2(1-\alpha)^2}w \quad (29)$$

Next, we solve for the quantity of CFRP produced by Toray and its rival in the Boeing phase. If Toray and Boeing sign the exclusive contract, each quantity changes as follows.

$$K_{TB}^* = \bar{K}_{TB},\ K_{RB}^* = 0,\ K_B^* = C \quad (30)$$

Then, each firm obtains the following profits:

$$\pi_{TB} = (P_0 - \bar{K}_{TB})\bar{K}_{TB} - c\bar{K}_{TB} \quad (31)$$

$$\pi_{RB} = 0 \quad (32)$$

The optimal solution of aluminium for Boeing is

$$A_B^* = -\frac{\alpha}{1-\alpha}\bar{K}_{TB} + \frac{1}{2a(1-\alpha)}P_0 - \frac{1}{2a^2(1-\alpha)^2}w \quad (33)$$

Using the solutions above, the optimal aircraft solution for Boeing is

$$Q_B^* = \frac{1}{2}\left\{P_0 - \frac{1}{a(1-\alpha)}w\right\} \quad (34)$$

On the other hand, the optimal aircraft solution for Airbus is

$$Q_A^* = \frac{1}{4}\left\{P_0 - \frac{1}{a(1-\alpha)}w\right\} \quad (35)$$

Thus, Boeing and Toray obtain the following profits in the subgame perfect Nash equilibrium:

$$\pi_B = \bar{K}_{TB}\left(\bar{K}_{TB} + w\frac{\alpha}{1-\alpha} - p_0\right) + \frac{1}{8}\left\{P_0 - \frac{1}{\alpha(1-\alpha)}w\right\}^2 \quad (36)$$

$$\pi_T = (p_0 - c - \bar{K}_{TB})\bar{K}_{TB} + \frac{1}{8}(p_0 - c)^2 \quad (37)$$

3.2. Non-exclusive contract case

Let us now solve the subgame perfect Nash equilibrium for the case where Boeing rejects the exclusive contract with Toray. First, we consider Airbus phase to solve for the optimal A_A to maximize its profits, given (K_B, A_B, K_A).

$$\max\ \pi_A = -a^2(1-a)^2A_A^2 - a^2(1-\alpha)\alpha K_A A_A + a(P_0 - Q_B - a\alpha K)(1-\alpha)A_A + a(P_0 - Q_B - a\alpha K_A)\mathrm{a}K_A - (p_0 - K_A)K_A - wA_A \quad (38)$$

Solving $\frac{\partial \pi_A}{\partial A_A} = 0$, we obtain the best response function of Airbus using aluminium to the CFRP from Toray and the rival:

$$R(A_A) = \frac{\alpha}{2a(1-\alpha)}\left\{-2a\alpha K_A + P_0 - Q_B + \frac{1}{a(1-\alpha)}w\right\} \quad (39)$$

Next, we solve for the optimal production of CFRP for each firm in the Airbus phase. In this case, because there is no leader, they compete in a Cournot competition. Thus, they simultaneously make their decision without knowing each other's production. We solve the optimal production K_{TA} for Toray to maximize its profits π_{TA}, given the rival's production K_{RA}.

$$\max \quad \pi_{TA} = -K_{TA}^2 + (p_0 - K_{RA} - c)K_{TA} \quad (40)$$

Solving $\frac{\partial \pi_{TA}}{\partial K_{TA}} = 0$, we obtain

$$K_{TA} = \frac{1}{2}(p_0 - K_{RA} - c) \quad (41)$$

On the other hand, the best response function of the rival to Toray is maximizing the profit below

$$\max \quad \pi_{RA} = -K_{RA}^2 + (p_0 - K_{TA} - c)K_{RA} \quad (42)$$

Solving $\frac{\partial \pi_{RA}}{\partial K_{RA}} = 0$, we obtain

$$K_{RA} = \frac{1}{2}(p_0 - K_{TA} - c) \quad (43)$$

The Nash equilibrium satisfies the relation equations (41) and (43) such that we obtain the solution below:

$$K_{TA}^* = K_{RA}^* = \frac{1}{3}(p_0 - c) \quad (44)$$

$$K_A^* = \frac{2}{3}(p_0 - c) \quad (45)$$

Then, Toray and the rival obtain the profits below:

$$\pi_{TA} = \pi_{RA} = \frac{1}{9}(p_0 - c)^2 \quad (46)$$

Using $R(A_A)$ and K_A^*, given (K_B, A_B), we obtain the best response function $R(Q_A)$:

$$R(Q_A) = \frac{1}{2}\left\{P_0 - Q_B - \frac{1}{a(1-\alpha)}w\right\} \quad (47)$$

Next we consider Boeing phase to solve for the optimal A_B to maximize π_B for any K_B, given the best response function above.

$$\max\ \pi_B = -\frac{1}{2}a^2(1-a)^2A_B^2 + \{-a^2(1-\alpha)\alpha K_B + \frac{1}{2}a(1-a)P_0 - \frac{1}{2}w\}A_B + \frac{1}{2}a\alpha\{P_0 - a\alpha K_B + \frac{1}{a(1-a)}w\}K_B - (p_0 - K_B)K_B \quad (48)$$

Solving $\frac{\partial \pi_B}{\partial A_B} = 0$, we obtain the best response function $R(A_B)$:

$$R(A_B) = \frac{\alpha}{1-\alpha}K_B + \frac{1}{2a(1-\alpha)}P_0 - \frac{1}{2a^2(1-\alpha)^2}w \quad (49)$$

Next, we solve for the optimal quantity of CFRP produced by Toray and its rival in the Boeing phase. In this phase, Boeing does not sign the exclusive contract; consequently, both CFRP firms compete to produce quantities in a Cournot competition. First, we solve for the optimal K_{TB} for Toray to maximize π_{TB}, given the rival's production K_{RB}.

$$\max \quad \pi_{TB} = -K_{TB}^2 + (p_0 - K_{RB} - c)B \quad (50)$$

Solving $\frac{\partial \pi_{TB}}{\partial K_{TB}} = 0$, we obtain

$$K_{TB} = \frac{1}{2}(p_0 - K_{RB} - c) \quad (51)$$

In addition, we solve for the rival's optimal production K_{RB} to maximize π_{RB}, given K_{TB}.

$$\max \quad \pi_{RB} = -K_{RB}^2 + (p_0 - K_{TB} - c)K_{RB} \tag{52}$$

Solving $\frac{\partial \pi_{RB}}{\partial K_{RB}} = 0$, we obtain

$$K_{RB} = \frac{1}{2}(p_0 - K_{TB} - c) \tag{53}$$

The Nash equilibrium is a solution to the relation equations (51) and (53). We obtain the solution below.

$$K_{TB}^* = K_{RB}^* = \frac{1}{3}(p_0 - c) \tag{54}$$

$$K_B^* = \frac{2}{3}(p_0 - c) \tag{55}$$

Thus, Toray and the rival obtain the profits below.

$$\pi_{TB} = \pi_{RB} = \frac{1}{9}(p_0 - c)^2 \tag{56}$$

By using the result above, we obtain the optimal aluminium A_B^* for Boeing as

$$A_B^* = -\frac{\alpha}{1-\alpha}\frac{2}{3}(p_0 - c) + \frac{1}{2a(1-\alpha)}P_0 - \frac{1}{2a^2(1-\alpha)^2}w \tag{57}$$

Thus, we obtain the optimal aircraft Q_B^* for Boeing and Q_A^* for Airbus:

$$Q_B^* = \frac{1}{2}\left\{P_0 - \frac{1}{a(1-\alpha)}w\right\} \tag{58}$$

$$Q_A^* = \frac{1}{4}\left\{P_0 - \frac{1}{a(1-\alpha)}w\right\} \tag{59}$$

Therefore, in the Nash equilibrium, Boeing and Toray obtain the profits below.

$$\pi_B = \frac{2}{3}(p_0 - c)\left\{\frac{2}{3}(p_0 - c) + w\frac{\alpha}{1-\alpha} - p_0\right\} + \frac{1}{8}\left\{P_0 - \frac{1}{\alpha(1-\alpha)}w\right\}^2 \tag{60}$$

$$\pi_T = \frac{2}{9}(p_0 - c)^2 \tag{61}$$

3.3. Condition for success of exclusive contract

Let us now look at the condition under which Boeing signs the exclusive contract offered by Toray. That condition requires that Boeing and Toray obtain higher profits in the exclusive contract case than that in the non-exclusive contract case.

Comparing Eqns. (36), (37), (60) and (61), the following conditions need to be met $\pi_B^E \geq \pi_B^N$ for Boeing and $\pi_T^E \geq \pi_T^N$ for Toray, where, π_i^E and π_i^N is profits in the exclusive and non-exclusive contracts, respectively, for Boeing and Toray.

By satisfying both conditions, Toray offers the CFRP $\bar{K}_{TB}$ for satisfying the equations below;
From $\pi_B^E \geq \pi_B^N$,

$$\bar{K}_{TB} \leq \frac{1}{3}(p_0 + 2c) - \frac{\alpha}{1-\alpha}w, \bar{K}_{TB} \geq \frac{2}{3}(p_0 - c) \tag{62}$$

Additionally, from $\pi_T^E \geq \pi_T^N$,

$$\frac{6-\sqrt{22}}{12}(p_0 - c) \leq \bar{K}_{TB} \leq \frac{6+\sqrt{22}}{12}(p_0 - c) \tag{63}$$

Satisfying the above two equations, a boundary condition to sign the exclusive contract exists as

$$\frac{2}{3}(p_0 - c) \leq \bar{K}_{TB} \leq \frac{6+\sqrt{22}}{12}(p_0 - c) \tag{64}$$

In this condition, Toray's best offer is the sum of the quantity when Toray competes with its rival in a Cournot competition or slightly larger than that level.

4. Conclusion

Our results show that Toray had a greater incentive to offer larger amounts of production of CFRP than just the amount they would cover the rival's production in the market, in which they had to accept reduced profits to be accepted by Boeing. This is good for Boeing because of the low price.

In 2010, when Toray signed the contract to provide CFRP for Airbus A350XWB, Hexel and Cytec, in the US, were already supplying to Airbus. Thus, for supplying to Airbus, Toray was the third provider and needed to follow these two firms. To turn around this game, Toray needed to canters around obtaining the know-how in the Boeing phase. Our theoretical analysis suggests one possible scenario such that Toray joins the Airbus market to become the leader by applying the know-how from Boeing in the real world.

Applying this strategy to the general case study of material providers, when new technology is innovated, the best response strategy is for the firm who provides it to become the largest firm and leader in that market by producing much amounts of production and reducing the price. This strategy induces higher profits for both material providers and users. The exclusive contract is the useful and rational strategy as "system lock-in."

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