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Open Source and Intertemporal Market Competition under Network Effects ☆

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Abstract: This study analyzes a firm's decision to adopt an open source strategy in the development of a primary system product that has an indirect network effect on complementary accessory products, and evaluates its impact on market competition and social welfare. It shows that firms are likely to switch from a proprietary development strategy to an open source strategy as the network effect decreases, and a firm's strategy also depends on consumers' attitude toward future utility. This result implies that the presence of open source systems can benefit proprietary firms due to consumers' higher willingness-to-pay for accessory products, and can lead to greater industry profit and social welfare. This study also shows that when the system development cost is non-negligible, firms prefer an open source strategy due to the cost-saving effect, but society is worse off due to a fragmented market with multiple system products.

JEL classifications: L14, L15, L17, L86

Keywords: Hotelling model, packaged goods, network effect, forward-looking consumers

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1. Introduction

The success of open source software and its unique innovation process have attracted many researchers to study this new "private-collective" innovation approach in markets dominated by proprietary innovation systems (Lerner and Tirole, 2005; von Krogh and von Hippel, 2006). Free sharing and collaborative improvement have enabled several open source software products to successfully compete with proprietary products, and even to dominate in some markets such as web servers (Apache) and mobile phone operating systems (Android). Several studies investigate why for-profit firms such as IBM participate in and contribute to open source projects, and how competition between proprietary firms and open source firms evolves in the market (Casadesus-Masanell and Llanes, 2011; Cheng et al., 2011). Firms often rely on the open source innovation model to speed up the development of high-quality products, reduce development costs, utilize external expertise, and preempt a technology standard in emerging areas (West, 2003; Bonaccorsi and Rossi, 2006).

The objective of this study is to provide new insights about the role of an open source strategy on market competition and social welfare. We will answer the following questions: (i) Can firms obtain strategic advantage by adopting an open source strategy and, if so, under what conditions? (ii) Will the presence of open source firms always lead to intense competition and decrease total industry profit? (iii) How do market equilibria and social welfare change with the presence of open source firms?

By building a three-stage duopoly model in which firms can develop both primary system products and complementary accessory products, this study analyzes a firm's decision to adopt an open source strategy under different market environments. Two firms first decide whether to adopt a proprietary strategy or an open source strategy in the development of a system product, and then they set the prices of a system product and a complementary accessory product. Under the open source strategy, a rival firm can provide accessory products that work with the system. On the other hand, a firm with a proprietary strategy enjoys a full monopoly over the provision of accessory products. The firm's decision critically depends on the profits in the accessory market, especially on the degree of the network effect and consumers' forward-looking behavior (Katz and Shapiro, 1985; Kristiansen, 1998; Haruvy et al., 2008).

The modeling framework of this study differs significantly in several aspects from that of existing studies. First, this study analyzes firms' choice between proprietary and open source strategies (Shy and Thisse, 1999; Casadesus-Masanell and Llanes, 2011). Several existing studies consider a duopoly model in which a for-profit firm competes with a non-profit open source firm or organization; these studies show that proprietary and open source firms can coexist (Mustonen, 2003, 2005; Casadesus-Masanell and Ghemawat, 2006) or that proprietary firms can eventually prevail in the market (Lanzi, 2009; Athey and Ellison, 2014). These studies regard an open source firm as a passive competitor, and thus the firm's choice of an open source strategy is not explicitly addressed. On the other hand, this study focuses on a firm's strategic choice in the development of a system product under competitive market environments and examines how its strategy affects market equilibrium and social welfare.

Second, this study considers a packaged product (a system product and an accessory product) in which firms can provide accessory products for rival firms' open source system products. Existing studies typically consider bundled products that are sold as a single unit by a single firm (Llanes and de Elejalde, 2013; Li et al., 2018), and firms cannot provide rival firms' complementary products. Their setting eliminates the relationship between system development strategy and subsequent competition in the accessory market (Arora and Bokhari, 2007). In practice, however, consumers often purchase accessory products after acquiring a system product (Katz and Shapiro, 1994; Mariñoso, 2001), and open source firms tend to sell system products and accessory products separately (Mustonen, 2003). This study allows firms to sell each type of product separately so that firms can compete in the accessory market of an open source system as well as in the system market itself.

Lastly, unlike previous studies that focus on the direct network effect (Casadesus-Masanell and Ghemawat, 2006; Chen et al., 2011, Li et al., 2018), this study considers the indirect network effect in which the installed base of system products helps firms appropriate profits from accessory products (Gandal, 2002). Given the typical open source business model, analysis of the indirect network effect can help explain how financially constrained firms can gain a competitive advantage in accessory markets through an open source strategy.

This study finds that open source systems can bring strategic advantage to firms, depending on the degree of network effect and consumers' forward-looking behavior. When the network effect is strong, both firms are likely to adopt a proprietary strategy. However, one firm may switch to an open source strategy if the network effect is weak. For an intermediate network effect, the market equilibrium depends on consumers' attitude toward future utility: proprietary systems are likely to be served when consumers are myopic; open source systems appeal to forward-looking consumers. If the system development cost is non-negligible, an open source strategy is more appealing to firms due to its cost-saving effect, but society is worse off due to a fragmented market with multiple system products.

Existing studies show that the presence of open source systems is likely to improve consumer surplus and social welfare but erode firms' profits due to intense competition (Bitzer, 2004; Casadesus-Masanell and Ghemawat, 2006; Tesoriere and Balletta, 2017). However, this study shows that the presence of an open source system can strictly increase total industry profit compared to a market with only proprietary systems. When the network effect is weak or consumers are forward-looking, firms can make a higher profit by adopting a single open source system to avoid market fragmentation. Even if two open source systems compete in the market, firms can exercise price discrimination by providing two versions of accessory products, resulting in higher total industry profit.

The remainder of this study is organized as follows. After a discussion of the basic assumptions and main features of the duopoly model in Section 2, Section 3 analyzes the system-accessory provision subgame under different combinations of system development strategies. Section 4 presents the subgame perfect market equilibria under different parameter values and examines social welfare. Section 5 extends the model by considering non-negligible system development cost. The conclusion follows in Section 6.

2. Model

2.1. Firm's Decision

Consider an environment in which consumers derive utility by consuming a set of two products, a primary system product and a complementary accessory product. The products are characterized by "one-way essential complements" in that consumers can derive utility from the system product alone but not from the accessory product alone (Chen and Nalebuff, 2006). Firm *A* and Firm *B* can develop and provide both products, and they are located at 0 and 1, respectively, on a Hotelling line. Each firm's decision is to adopt an appropriate strategy of developing a system product either from a proprietary strategy or from an open source strategy. Given its and the rival firm's choice of system development strategy, each firm then determines the provision of accessory products, which are always proprietary.

If a firm decides to adopt a proprietary strategy by not disclosing key source code or standards, the other firm cannot develop complementary accessory products that work with the proprietary system due to technical or legal barriers. Only the system developer can provide accessory products for its system. If, on the other hand, a firm adopts an open source strategy, the rival firm can provide accessory products for the open source system and compete in the accessory market with the system developer. If two firms provide open source systems, each firm has to provide two versions of incompatible accessory products: one for its own system users and the other for the rival firm's system users. We assume the cost of developing system products or providing accessory products is zero for both firms.

We consider a three-stage competition game between the two firms. In Stage 0, Firms *A* and *B* simultaneously decide their system product development strategies. In Stage 1, after observing the system development strategy of the other firm, each firm simultaneously sets its system price, $p_i \geq 0$, where $i=A, B$, and consumers purchase a system product from either firm in anticipation of the availability and price of accessory products in the next stage. In Stage 2, after observing consumers' purchase of system products, each firm simultaneously decides whether to provide accessory products and, if so, sets the corresponding accessory price, $r_i \geq 0$.

2.2. Demand

A group of heterogeneous consumers are uniformly distributed over [0, 1] on the Hotelling line, and the total mass of consumers is one. From the purchase of a system product in Stage 1, the utility of a consumer located at $x \in [0, 1]$ is

$$u_1 = \begin{cases} \beta - x - p_A & \text{if she buys a system product from Firm } A \\ \beta - (1-x) - p_B & \text{if she buys a system product from Firm } B, \end{cases}$$

where β denotes the consumer's valuation of the system product and $p_i \geq 0$ is the price of a system product developed by Firm *i*. We assume that β is sufficiently large so that all consumers purchase system products from either firm.

Consumer *y* who purchased Firm *A*'s system product in Stage 1 is called an *A-user*. If Firm *A* adopts an open source strategy and Firm *B* provides accessory products for Firm *A*'s system product, *A*-user's utility from purchasing an accessory product in Stage 2 is

$$u_{A2} = \begin{cases} \delta N_A - y - r_A & \text{if she buys an accessory from Firm } A \\ \delta N_A - (1-y) - \tilde{r}_A & \text{if she buys an accessory from Firm } B, \end{cases}$$

where $\delta > 0$ is the network effect factor of a system product on an accessory product, N_A is the number of consumers who purchased Firm *A*'s system product, $r_A \geq 0$ is the price of an accessory product provided by Firm *A*, and $\tilde{r}_A \geq 0$ is the price of an accessory product provided by Firm *B* for Firm *A*'s system product. δN_A indicates the total benefit of the network effect from using Firm *A*'s system product. Similarly, the utility of *B*-user who purchases an accessory product in Stage 2, given that Firm *B* adopts an open source strategy, is

$$u_{B2} = \begin{cases} \delta N_B - (1-y) - r_B & \text{if she buys an accessory from Firm } B \\ \delta N_B - y - \tilde{r}_B & \text{if she buys an accessory from Firm } A. \end{cases}$$

We assume that the network effect factor satisfies $\delta \geq 2$, to rule out partial coverage of accessory markets. For each case of the development strategies discussed in the next section, the full coverage of accessory markets can be verified in equilibrium by this assumption.

Consumers' purchase decision of system products in Stage 1 depends on the total utility obtained from both stages. We define the discount factor as $0 \leq \lambda \leq 1$, which can be interpreted as the weight consumers put on future utility when making the system purchase decision (Chevalier and Goolsbee, 2009; Sun et al., 2003). Thus, the total utility of a consumer is expressed as

$U = u_1 + \lambda u_{i2}$, where *i* = *A*, *B*. If λ is close to zero, the consumer tends to be myopic in that he cares more about the utility from Stage 1 when purchasing a system product. On the other hand, the consumer assigns equal weights to the utilities in both stages of the system purchase decision if λ approaches one.

3. System-Accessory Provision Subgame

For each combination of system development strategies made in Stage 0, the problem is essentially a two-stage system-accessory provision game at the start of Stage 1. In this section, we derive the equilibrium for each combination of subgame by backward induction. We first solve the prices of accessory products provided by each firm in Stage 2 given the prices of system products, and then solve the prices of system products in Stage 1.[1]

3.1. Case 1: Two Proprietary Systems

We first consider the case where both firms adopt a proprietary strategy in the development of a system product. Due to the closed nature of system products, each firm cannot provide accessory products for its rival's system product. In Stage 2, Firm *i* is faced with N_i users who have purchased its system product in Stage 1, and sets a monopoly price r_i for its accessory product. Among *A*-users, consumer *y* is indifferent to buying an accessory product from Firm *A* or not buying at all: $\delta N_A - y - r_A = 0$. The demands for accessory products provided by Firm *A* and by Firm *B* are $n_A(\equiv y) = \delta N_A - r_A$ and $n_B(\equiv 1 - y) = \delta N_B - r_B$, respectively.

In Stage 2, each firm is the monopoly provider of the accessory product, and consumers'

[1] In solving the equilibrium in each subgame, we consider the full coverage of the accessory market and then verify it in equilibrium except for Case 1. For Case 1, we start with the partial coverage and then verify the full market coverage.

demand for the monopoly's system product is locked in. Firm *i* faces a constrained profit maximization problem as follow:

$$\max_{r_i} \pi_{i2} = r_i n_i \qquad (1)$$
$$s.t.\ \ n_i \le N_i.$$

Solving Equation (1) for Firm *A* and Firm *B* leads to the following solutions in Stage 2.

$$r_A^* = (\delta - 1) N_A, \quad r_B^* = (\delta - 1) N_B, \quad n_A^* = N_A, \quad n_B^* = N_B,$$
$$\pi_{A2}^* = (\delta - 1) N_A^2, \quad \pi_{B2}^* = (\delta - 1) N_B^2. .$$

Each firm's accessory prices depend on the population of consumers who have purchased its system product (N_i), as well as the network effect (δ).

In Stage 1, the consumer located at *x* is indifferent to buying a system product from Firm *A* or Firm *B* if the total utility from both stages satisfies the following equation.

$$\left[\beta - x - p_A\right] + \lambda\left(\delta x - x - r_A\right) = \left[\beta - (1-x) - p_B\right] + \lambda\left[\delta(1-x) - (1-x) - r_B\right].$$

Since both system products are proprietary, the demand for Firm *A*'s accessory product in Stage 2 is simply *x*. Using the solutions in Stage 2 derived above ($r_i^* = (\delta - 1) N_i$ and $x = N_i$), we can show that the marginal consumer *x*'s utility in Stage 2 is zero. Thus, the demands for system products developed by Firms *A* and Firm *B* in Stage 1 are, respectively

$$N_A = (1 + p_B - p_A)/2 \qquad \text{and} \qquad N_B = (1 + p_A - p_B)/2.$$

For the case of two proprietary system products, each firm charges a monopoly price on its accessory products. Since the marginal consumer receives zero utility in Stage 2, his purchase decision of a system product is simply based on the utility from Stage 1. In Stage 1, Firm *i* sets the price of a system product p_i to maximize the total profit.

$$\max_{p_i} \pi_i = p_i N_i + \pi_{i2}^*$$
$$s.t.\ \ N_i \le 1. \tag{2}$$

Solving Equation (2) for Firm *A* and Firm *B* leads to the following subgame equilibrium.

$$\begin{aligned} &p_A^* = p_B^* = 0, && r_A^* = r_B^* = (\delta - 1)/2, \\ &N_A^* = N_B^* = n_A^* = n_B^* = 1/2, && \pi_A^* = \pi_B^* = (\delta - 1)/4. \end{aligned} \tag{3}$$

Lemma 1. *If both firms compete with a proprietary strategy, they give away their system products for free and set the same prices for accessory products by evenly sharing the market. The price of accessory products and firms' profits increase with the network effect* δ*.*

Proof. See Appendix.

When both firms adopt a proprietary strategy, the competition is concentrated in Stage 1, because each firm becomes a monopoly provider of accessory products to its system's users in Stage 2. Competitive pressure to take advantage of the network effect forces each firm to give away its system products for free in Stage 1 (i.e., $p_i = 0$) and make profits from selling accessory products in Stage 2. When the network effect is strong, consumers are willing to pay more for accessory products and each firm can charge a high price. This result is similar to that of Haruvy et al. (2008) who find that a proprietary firm has a strong incentive to set a low price to make a high profit from complementary products under positive network effect.

3.2. Case 2: Proprietary System and Open Source System

We consider the second case in which Firm *A* maintains a proprietary strategy but Firm *B* adopts an open source strategy.[2] The price of Firm *B*'s system product is zero under the open source strategy. In Stage 2, Firm *A* can provide accessory products for both types of system products,

[2] We skip the symmetric case where Firm *A* adopts an open source strategy and Firm *B* a proprietary strategy.

while Firm *B* can provide accessory products only for its own system users. *B*-user *z* is indifferent to buying accessory products from either Firm *A* or Firm *B* if $\delta N_B - z - \tilde{r}_B = \delta N_B - (1-z) - r_B$, where $z \in [1 - N_B, 1]$. The demands by *B*-users for accessory products provided by Firm *A* and Firm *B* are, respectively,

$$\tilde{n}_B = \frac{r_B - \tilde{r}_B - 1}{2} + N_B \quad \text{and} \quad n_B = \frac{1 - r_B + \tilde{r}_B}{2}$$

In Stage 2, Firm *A*'s profit comes from selling accessory products to *A*-users ($r_A n_A$) and to *B*-users ($\tilde{r}_A \tilde{n}_A$). Firm *A* is the monopoly provider of accessory products to *A*-users, and its profit maximization problem for *A*-users in Stage 2 is

$$\max_{r_A} \pi_{A2} = r_A\left(\delta N_A - r_A\right) \qquad (4)$$
$$s.t.\ \ n_A \le N_A.$$

Solving Equation (4) leads to the following solutions for the accessory market for *A*-users.

$$r_A^* = (\delta - 1)N_A, \qquad n_A^* = N_A, \qquad \pi_{A2}^* = (\delta - 1)N_A^2 \ .$$

For *B*-users, both Firm *A* and Firm *B* compete to sell accessory products in Stage 2. The profit maximization problems of Firm *A* and Firm *B* for *B*-users are, respectively

$$\max_{\tilde{r}_B} \tilde{\pi}_{A2} = \tilde{r}_B \tilde{n}_B = \tilde{r}_B\left(\frac{r_B - \tilde{r}_B - 1}{2} + N_B\right) \qquad (5a)$$
$$s.t.\ \ \tilde{n}_B \le N_B$$

and

$$\max_{r_B} \pi_{B2} = r_B n_B = r_B\left(\frac{1 - r_B + \tilde{r}_B}{2}\right) \qquad (5b)$$
$$s.t.\ \ n_B \le N_B.$$

Solving Equations (5a) and (5b) leads to the following solutions for the accessory market for *B*-users.

$$\tilde{r}_B^* = \frac{4N_B - 1}{3}, \qquad r_B^* = \frac{2N_B + 1}{3}, \qquad \tilde{n}_B^* = \frac{4N_B - 1}{6},$$

$$n_B^* = \frac{2N_B + 1}{6}, \qquad \pi_{A2}^* = \frac{(4N_B - 1)^2}{18}, \qquad \pi_{B2}^* = \frac{(2N_B + 1)^2}{18}.$$

In Stage 1, the marginal consumer *x* is indifferent to buying a system product from Firm *A* or from Firm *B* if the following equation is satisfied.

$$[\beta - x - p_A] + \lambda\left[\delta x - x - r_A^*\right] = [\beta - (1 - x)] + \lambda\left[\delta(1 - x) - x - \tilde{r}_B^*\right]. \tag{6}$$

If the marginal consumer x adopts a proprietary system, he can purchase the accessory product only from the proprietary firm. If he adopts an open source system, on the other hand, he can buy the accessory product from either firm. The left-hand side (LHS) of Equation (6) is the marginal user *x*'s total utility if purchasing a proprietary system product, and his utility from Stage 2 is zero from Case 1. The right-hand side (RHS) is his total utility if purchasing an open source system product in Stage 1. The second term of the RHS is the utility from Stage 2, which depends on the price of accessory products provided by Firm *A*, $\tilde{r}_B^* = (4N_B - 1)/3$. The demands for system products developed by Firm *A* and Firm *B* in Stage 1 are, respectively

$$N_A = \frac{3(\lambda\delta - \lambda - 1 + p_A)}{3\lambda\delta - \lambda - 6} \quad \text{and} \quad N_B = \frac{2\lambda - 3 - p_A}{3\lambda\delta - \lambda - 6}.$$

In Stage 1, Firm *A* sets p_A to maximize the total profit from selling its system products and accessory products to both *A*-users and *B*-users.

$$\max_{p_A} \pi_A = p_A N_A + \pi_{A2}^* + \tilde{\pi}_{A2}^*$$
$$s.t.\ \ 0 \le N_A \le 1. \tag{7}$$

Solving Equation (7) leads to the corresponding subgame equilibrium (See Appendix for the equilibrium) and Lemma 2 as follow.

Lemma 2. *Suppose one firm maintains a proprietary strategy and the other firm adopts an open source strategy.*

(i) If $\delta \geq 25/9$ *and* $0 \leq \lambda \leq \lambda_2$*, the proprietary firm takes a smaller market share in the system market with zero system price but makes a higher profit from both markets than the open source firm does.*

(ii) If $2 \leq \delta < 25/9$ *or* $\lambda_2 < \lambda \leq 1$*, an open source system product dominates the system market and both firms make equal profit from the accessory market.*

(iii) The presence of an open source system product can benefit the proprietary firm if $2 \leq \delta < 3$ *or* $0 \leq \lambda \leq \lambda_1$*, where* $\lambda_1 = \frac{18\delta^2 - 52\delta + (10 - 6\delta)\sqrt{(\delta - 1)(9\delta - 19)} + 42}{27\delta^3 - 91\delta^2 + 89\delta - 17}$ *and* $\lambda_2 = \frac{9\delta - 25}{9\delta^2 - 22\delta + 17}$ *with* $\lambda_1 < \lambda_2$.

Proof. See Appendix.

When the network effect is strong ($\delta \geq 25/9$) and consumers are relatively myopic ($0 \leq \lambda \leq \lambda_2$), the proprietary firm uses an aggressive pricing strategy to expand its market share by setting $p_A = 0$ for the system product. However, it makes a higher profit than the open source competitor does due to its larger market share in the accessory market and consumers' higher willingness-to-pay for accessory products. When the network effect is weak ($\delta < 25/9$) or consumers are relatively forward looking ($\lambda_2 < \lambda \leq 1$), on the other hand, the proprietary firm lets the open source system occupy the entire market by charging a maximum price and makes a profit only from the accessory market. Instead of providing its proprietary system so that the market is fragmented with two incompatible systems, the proprietary firm is better off giving up its own system market and competing only in the accessory market.

Several existing studies argue that the presence of open source firms reduces the profits of proprietary firms due to intense competition (Bitzer, 2004; Casadesus-Masanell and Ghemawat, 2006; Lanzi, 2009). However, Lemma 2 (iii) implies that the proprietary firm can make a higher profit if the rival firm switches from a proprietary strategy to an open source strategy. When the network effect is relatively weak ($2 \leq \delta \leq 3$), the open source system is likely to prevent market fragmentation, and the proprietary firm can be better off. With the presence of an open source system, forward-looking consumers tend to adopt the open source system to enjoy less expensive accessory products and the proprietary firm is likely to suffer with a smaller market share of its product. With a larger market for the open source system, however, the proprietary firm can make a higher profit by selling accessory products to the open source system. As long as consumers are myopic enough ($0 \leq \lambda \leq \lambda_1$), the second effect dominates the first effect and the proprietary firm is better off with the presence of an open source system.

3.3. Case 3: Two Open Source Systems

We consider another case in which both firms adopt an open source strategy in the development of a system product. Each firm can provide two versions of accessory products: one for its system users and another for the rival's system users. In Stage 1, the price of each firm’s system products is zero by assumption: $p_A^* = p_B^* = 0$. In Stage 2, both *A*-users and *B*-users can purchase accessory products from either firm, and they are indifferent to buying accessory products from either firm if

$$\delta N_A - y - r_A = \delta N_A - (1-y) - \tilde{r}_A$$
$$\delta N_B - z - \tilde{r}_B = \delta N_B - (1-z) - r_B.$$

The demands for accessory products for each system are

$$n_A = \frac{\tilde{r}_A - r_A + 1}{2}, \quad \tilde{n}_B = (1 - N_A) - \frac{\tilde{r}_B - r_B + 1}{2}, \quad \tilde{n}_A = N_A - \frac{\tilde{r}_A - r_A + 1}{2}, \quad n_B = \frac{\tilde{r}_B - r_B + 1}{2} \;,$$

where $\tilde{n}_i$ is the demand by *i*-users for accessory products provided by the other firm. The profit maximization problem of firm *i* in the accessory market is (*i*, *j* = *A*, *B*),

$$\begin{aligned} &\max_{r_i, \tilde{r}_j} \pi_{i2} = r_i n_i + \tilde{r}_j \tilde{n}_j \\ &s.t. \;\; 0 \le n_i \le 1 \quad \text{and} \quad 0 \le \tilde{n}_j \le 1 \end{aligned} \tag{8}$$

Solving Equation (8) for Firm *A* and Firm *B* leads to the following solutions in Stage 2.

$$r_A^* = (2N_A + 1)/3, \quad \tilde{r}_A^* = (4N_A - 1)/3, \quad r_B^* = (3 - 2N_A)/3, \quad \tilde{r}_B^* = (3 - 4N_A)/3,$$
$$n_A^* = (2N_A + 1)/6, \quad \tilde{n}_A^* = (4N_A - 1)/6, \quad n_B^* = (3 - 2N_A)/6, \quad \tilde{n}_B^* = (3 - 4N_A)/6.$$

In Stage 1, the marginal consumer *x* is indifferent to choosing an open source system product from Firm *A* or from Firm *B* if the following equation is satisfied.

$$[\beta - x] + \lambda\left[\delta x - (1-x) - \tilde{r}_A^*\right] = [\beta - (1-x)] + \lambda\left[\delta(1-x) - x - \tilde{r}_B^*\right].$$

With two incompatible open source systems, each firm can provide accessory products to its rival's users and consumers can purchase accessory products from the either firm. Thus, the marginal user needs to balance between two options: adopting an open source system from one firm and buying an accessory product from the other, or vice versa[3]. The second terms in either side of the above equation are the utility from purchasing accessory products from the rival firms. This leads to $N_A = N_B = ½$, and the subgame equilibrium is summarized in Equation (9).

[3] When $N_i < 1/(1+\delta)$, all *i*-users purchase accessories only from Firm *i*, because buying from Firm *j* always makes them worse off even for $\tilde{r}_j = 0$, that is, $\delta N_i - (1-y) < 0$. And Firm *i* will set $r_i = (\delta - 1) N_i$ to maximize their profit. However, it is never an equilibrium because $(\beta - N_i) + 0 < [\beta - (1 - N_i)] + \lambda[\delta(1 - N_i) - N_i - \tilde{r}_j]$ always holds for the marginal user. So $N_i \ge 1/(1+\delta)$ is a possible equilibrium and any user's base utility from network externality in Stage 2 is no less than $\delta/(1+\delta)$, which is larger than $2/3$ for $\delta \ge 2$. Due to the symmetry of two firms, all users can always buy accessories from either firm.

$$r_A^* = r_B^* = 2/3, \qquad \tilde{r}_A^* = \tilde{r}_B^* = 1/3,$$
$$n_A^* = n_B^* = 1/3, \qquad \tilde{n}_A^* = \tilde{n}_B^* = 1/6, \qquad \pi_A^* = \pi_B^* = 5/18. \tag{9}$$

Lemma 3. *Suppose both firms adopt an open source strategy.*

(i) Both firm are better off compared with the case of two proprietary systems, if the network effect is very weak ($2 \le \delta < 19/9$).

(ii) Both firms are always worse off compared with the case where a single open source system dominates the market.

(iii) Both firms are worse off compared with the case of both proprietary and open source systems, if $\delta > \frac{39\sqrt{5}+33}{27\sqrt{5}-27}$ *and* $\frac{\left(27-9\sqrt{5}\right)\delta+15\sqrt{5}-33}{18\delta^2-24\delta-2} \le \lambda \le \lambda_2$.

The market outcome with two open source systems is similar to the outcome with two proprietary systems, in that (i) two incompatible system products exist, (ii) firms give away system products for free, and (iii) firms make profits only from accessory products by evenly sharing the market. However, the demand pattern in the accessory market is different between the two cases. Unlike the case with two proprietary systems, each firm provides accessory products to the rival firm's system users as well as its own system users if two open source firms compete in the market. Firms charge two different prices by providing two versions of accessory products: a high price to its system users and a low price to the rival's system users. This pricing behavior implies that having open source systems enables firms to implement *de facto* price discrimination. Firms do not need to lower the accessory price for their system users even if they are faced with competition. On the other hand, firms under two open source systems are worse off than in the case of a single open source system because an un-fragmented market with a single system product allows each firm to charge a higher price to accessory products.

4. Equilibria of the Competition Game and Welfare Analysis

With the solutions of different cases of the system-accessory provision subgame analyzed in the previous section, we can derive the subgame perfect Nash equilibrium of the entire competition game. By comparing the profits under different system development strategies in Table 1, we identify two possible subgame perfect Nash equilibria: a proprietary equilibrium in which both firms adopt a proprietary strategy, and a mixed equilibrium in which one firm adopts an open source strategy and the other firm, a proprietary strategy.

Insert [Table 1] here

Proposition 1.

(i) If the network effect is very strong ($\delta > 3$*), only a proprietary equilibrium exists.*

(ii) If the network effect is weak ($2 \leq \delta < 25/9$*), only a mixed equilibrium exists.*

(iii) If the network effect is in an intermediate range ($25/9 < \delta \leq 3$*), a proprietary equilibrium exists for a low discount factor (*$0 \leq \lambda \leq \lambda 2$*) and a mixed equilibrium exists for a high discount factor (*$\lambda_2 < \lambda \leq 1$*).*

(iv) In a mixed equilibrium, a single open source system always dominates the market.

[Figure 1 here]

As summarized in Figure 1, Proposition 1 illustrates the role of the network effect and consumers' attitude toward future utility in a firm's choice of system development strategy. The implications of Proposition 1 can be explained through the example of Microsoft's strategy for the Windows operating system (OS) versus its big data project (Henschen, 2011). Microsoft continues to keep its popular Windows OS proprietary and competes with other proprietary rival products (e.g., Mac OS) and open source rival products (e.g., Linux). The desktop OS market exhibits a very strong network effect, and Microsoft makes a high profit by making its Windows OS proprietary and selling complementary products like MS Office Suite in the accessory market. On the other hand, Microsoft adopts an open source strategy in the big data processing project by abandoning its own product and supporting Hadoop, the leading *de facto* industry standard open source platform. The big data platform is still an emerging market with a weak network effect, and Microsoft supports a popular open source platform to attract more consumers to the complementary service market.

Proposition 1 also implies that consumers' attitude toward future utility also affects a firm's development strategy when the network effect is not a dominant factor. While Linux has a small market share in the desktop OS market (3.3% as of August 2017), it dominates the supercomputer OS market with more than 95% market share as of August 2017. The main customers of supercomputers are firms that tend to be forward-looking and choose open source products based on the price of complementary service products. On the other hand, consumers in the desktop market are less forward-looking and are likely to choose proprietary products.

The industry profit and social welfare under the proprietary equilibrium are $\Pi_P^* = (\delta - 1)/2$ and $W_P^* = \beta - (1-\lambda)/4 + (\delta - 1)/2$, respectively. Similarly the corresponding values under the mixed equilibrium are $\Pi_M^* = 1$ and $W_M^* = \beta + \lambda(\delta - 5/4) + 1/2$, respectively. Comparison of the two equilibria leads to the following proposition.

Proposition 2.

(i) The presence of an open source system not only makes its proprietary rival firm better off, but also increases the total industry profit if $2 \le \delta \le 3$.

(ii) The presence of an open source system product increases social welfare if $2 \leq \delta \leq 5/2$ or $(2\delta - 5)/(4\delta - 6) \leq \lambda \leq 1$.

When the market is served by a single open source system instead of two proprietary systems, the increased installed base of system products increases consumers' willingness-to-pay for accessory products and both firms are better off. In addition, while competition between two proprietary systems may lead to market fragmentation, availability of an open source system may avoid market fragmentation through a firm's coordination with the rival firm. Consumers are better off with less expensive system products, and firms are better off with higher profits in the accessory market, leading to higher social welfare if the network effect is weak or consumers are forward-looking. Von Engelhardt and Maurer (2012) argue that an open source business model helps avoid duplication of investment and encourages firms' R&D investment, leading to improved social welfare. Our study provides the rationale of this argument in that the network effect enables open source firms to capture larger profits in the accessory markets. This insight is also consistent with Llanes and de Elejalde (2013) who propose that government should subsidize open source projects to improve social welfare.

5. Extension: System Development Cost

Our model has assumed a zero development cost of system products and shown that the presence of an open source strategy can bring a strategic advantage to a proprietary firm. Another important advantage of developing an open source system is the cost-saving effect, which can be quite attractive to small and medium-sized firms with capital constraint (Caulkins et al., 2013). This section introduces a non-negligible system development cost and examines how the cost-saving effect affects firms' development strategy and market equilibrium. We assume that a firm incurs an identical development cost of $C > 0$ if it adopts a proprietary strategy, but zero cost if it pursues an open source strategy. To simplify the analysis, we further assume $2 \leq \delta \leq 35/9$.

With positive development costs, the competition game is represented in Table 2. An open source equilibrium in which both firms adopt an open source strategy can be another possible equilibrium when the system development cost is non-negligible. Proposition 3 summarizes the equilibrium, which is illustrated in Figure 2.

Proposition 3.

(i) *If the system development cost is low* ($0 < C \leq 2/9$), *either a mixed equilibrium or a proprietary equilibrium exists depending on the discount factor. The open source firm makes a higher profit than its proprietary rival in the mixed equilibrium.*

(ii) If the system development cost is high ($C > 2/9$), *either an open source equilibrium or a proprietary equilibrium exists depending on the discount factor. An open source equilibrium may lead to a lower industry profit and social welfare than a proprietary equilibrium.*

Proof. See Appendix.

When the system development cost is low but positive ($0 < C \leq 2/9$), a firm is likely to choose an open source strategy to save the development cost. As the development cost increases ($C > 2/9$), both firms are likely to adopt an open source strategy. However, under the fragmented market with two open source systems, the total industry profit and social welfare are lower than in the case of a mixed equilibrium. A large cost-saving incentive makes it difficult for firms to cooperate to adopt a single open source system, leading to a fragmented market. For example, in the early development stage, firms adopted different, incompatible, versions of the Linux kernel, leading to fragmented markets. Later, the Linux community actively coordinated to develop a compatible kernel to expedite the development of its product (Moody, 2009)

6. Conclusion

How a market evolves with the presence of open source firms has been an interesting issue in recent decades for both researchers and policy makers. In several industries such as telecommunication and computer software, innovation and its commercialization might have been slowed due to the problem of “patent thickets” in which firms have to navigate overlapping sets of patents and obtain licenses from multiple patentees (Shapiro, 2001). The unique process of open source innovation and its nature of free sharing and contribution may potentially solve this problem. This study analyzes a firm's incentive to adopt an open source strategy and its impacts on market competition and social welfare. In a market with a package product (system product and accessory product), this study develops a three-stage duopoly model in which two firms compete in the development and provision of system and accessory products.

This study finds that market equilibrium depends on the size of the network effect and consumers’ attitude toward future utility. Two proprietary systems coexist in the market if the network effect is strong, but only one open source system dominates the market if the network effect is weak. For an intermediate range of the network effect, the market is likely to be served by a single open source system if consumers are forward-looking, and by two proprietary systems if consumers are myopic. Contrary to the common perception of negative effects of open source system on firms’ profits, this study shows that the presence of an open source system can increase total industry profit and social welfare by avoiding a fragmented system market. If the system development costs are non-negligible, firms are more likely to adopt an open source strategy, but the general qualitative results still hold.

This study can provide a few managerial and policy insights. It illustrates that an open source strategy is a rational choice for firms that compete in an industry with a weak network effect and a high system development cost. With an open source system, firms may sacrifice the profit from the system market, but can be compensated more from the accessory market by avoiding market fragmentation. In addition, government may choose to encourage firms to adopt the open source standard by providing a subsidy or tax reduction when the industry has a weak network or high development cost. A high system development cost can make an open source strategy more attractive, but this cost-saving advantage may also lead to market fragmentation. Government or open source promoting organizations such as the Open Source Initiative (OSI) can expedite the coordination process by providing standardized open source licenses and preventing market fragmentation.

For simplicity and clarity, this study assumes the price of system products is non-negative, but the consideration of a negative price, or subsidy, of the system product can be a possible extension. Under a strong network effect, firms have an incentive to provide a subsidy to increase the installed base and make more profits in the accessory market. This would intensify competition in the system market, and firms adopting a proprietary strategy may end up having zero profits in equilibrium. Another extension can be the sequential entry game. Our model assumes that two firms simultaneously decide the system development strategy without observing the other firm's decision. If an entrant determines the system development strategy after observing the incumbent's decision, the chance of market fragmentation can be reduced and an open source strategy can be more attractive.

Appendix

Proof of Lemma 1

With the symmetry of both firms' problems, Equation (2) in equilibrium reduces to

$$\max_{p_i} \pi_i = p_i \left(\frac{1 + p_j - p_i}{2} \right) + \pi_{i2}^*$$

with the solution $p_i^* = p_j$ for $i, j = A, B$. By the Karush-Kuhn-Tucker (KKT) conditions, if $p_A > 0$ and $\partial L_A / \partial p_A = 0$, we have $p_A = 1 - 2(\delta - 1) < 0$ due to the assumption of $\delta \geq 2$, and there is a contradiction. If $p_A = 0$ and $\partial L_A / \partial p_A < 0$, there is no contradiction and we have $p_A^* = 0$. The same logic applies to $p_B^* = 0$. The second-order conditions are satisfied as well. The subgame equilibrium is summarized as

$$\begin{aligned} &p_A^* = p_B^* = 0, && r_A^* = r_B^* = (\delta - 1)/2, \\ &N_A^* = N_B^* = n_A^* = n_B^* = 1/2, && \pi_A^* = \pi_B^* = (\delta - 1)/4. \end{aligned}$$

Proof of Lemma 2

(1) If $1/(\delta - 1) < \lambda \leq 1$, we have that $\beta - x - p_A > \beta - (1 - x) + \lambda \left[\delta(1 - x) - x - \frac{4(1 - x) - 1}{3} \right]$ for any $x \in [0,1]$, and all consumers adopts an open source system. Thus, Equation (6) does not hold and the constraint of (7) cannot be satisfied if $p_A \geq 0$. Since $N_A^* \geq 0$, we have $n_A^* = N_A^* = 0$ as long as $p_A^* \geq 0$ in equilibrium. We have $r_B^* = \tilde{r}_B^* = 1$, $n_B^* = \tilde{n}_B^* = 1/2$ and $\pi_A^* = \pi_B^* = 1/2$.

(2) If $0 \leq \lambda \leq 1/(\delta - 1)$, the Lagrangian function of the maximization problem from Equation (7) is

$$\max_{p_A} L = p_A\left(\frac{3(\lambda\delta-\lambda-1+p_A)}{3\lambda\delta-\lambda-6}\right)+(\delta-1)\left(\frac{3(\lambda\delta-\lambda-1+p_A)}{3\lambda\delta-\lambda-6}\right)^2$$
$$+\frac{1}{18}\left(3-4\left(\frac{3(\lambda\delta-\lambda-1+p_A)}{3\lambda\delta-\lambda-6}\right)\right)^2+\mu(\lambda+1-\lambda\delta-p_A)$$

By the KKT conditions, the following equations should be satisfied.

$$\frac{\partial L}{\partial p_A}\le 0,\quad p_A\ge 0,\quad \frac{\partial L}{\partial p_A}p_A=0,\quad \frac{\partial L}{\partial \mu}\ge 0,\quad \mu\ge 0,\quad \frac{\partial L}{\partial \mu}\mu=0$$

We discuss the solutions for two possible scenarios.

Scenario 1: Suppose $p_A=0$.

(i) If $\partial L/\partial\mu>0$ and $\mu=0$, we need $\lambda<1/(\delta-1)$, which always holds for this case. We also need $\partial L/\partial p_A<0$, which requires $44-18\delta+27\lambda-59\delta\lambda+18\delta^2\lambda+3\lambda^2-12\delta\lambda^2+9\delta^2\lambda^2<0$. This inequality holds only when $\delta^+<\delta<22/9$ and $\lambda^+\le\lambda<\lambda^\#$, or $\delta>22/9$ and $0\le\lambda<\lambda^\#$, where $$\lambda^+=\frac{-18\delta^2+59\delta-\sqrt{324\delta^4-1476\delta^3+2005\delta^2-858\delta+201}-27}{18\delta^2-24\delta+6},$$

$\lambda^\#=\dfrac{-18\delta^2+59\delta+\sqrt{324\delta^4-1476\delta^3+2005\delta^2-858\delta+201}-27}{18\delta^2-24\delta+6}$, and δ^+ is the bigger root of $324\delta^4-1476\delta^3+2005\delta^2-858\delta+201=0$ and $2<\delta^+<22/9$. The profit is

$$\pi^*_{A(1)}=\frac{18\lambda^2\delta^3-53\lambda^2\delta^2+48\lambda^2\delta-9\lambda^2-36\lambda\delta^2+76\lambda\delta-48\lambda+18\delta-14}{2(3\lambda\delta-\lambda-6)^2}$$

(ii) If $\partial L/\partial\mu=0$ and $\mu>0$, we have $\lambda=1/(\delta-1)$. Plugging it into $\partial L/\partial p_A$ leads to $4(\delta-1)/(3\delta-5)-\mu$. Thus, $\partial L/\partial p_A<0$ holds when $\mu>4(\delta-1)/(3\delta-5)>0$, and the profit is $\pi^*_{A(2)}=1/2$.

Scenario 2: Suppose $p_A>0$, so that $\partial L/\partial p_A=0$.

(i) If $\mu>0$, then $\partial L/\partial\mu=0$ and $p_A=1-\lambda(\delta-1)$. Plugging it into $\partial L/\partial p_A=0$ leads to

$\mu = \dfrac{3\lambda\delta - 3\lambda + 1}{\lambda - 3\lambda\delta + 6}$, and thus $\mu > 0$ always holds. We have $\pi^*_{A(2)} = 1/2$.

(ii) If $\mu = 0$, we obtain $p^*_A = \dfrac{27\lambda - 18\delta + 3\lambda^2 + 9\lambda^2\delta^2 - 59\lambda\delta + 18\lambda\delta^2 - 12\lambda^2\delta + 44}{6\lambda - 18\delta - 18\lambda\delta + 38}$ and $\dfrac{\partial L}{\partial \mu} = \dfrac{9\lambda^2\delta^2 - 12\lambda^2\delta + 3\lambda^2 - 15\lambda\delta + 17\lambda - 6}{6\lambda - 18\delta - 18\lambda\delta + 38}$. We have $p^*_A > 0$ and $\partial L / \partial \mu > 0$ when $\delta^+ < \delta < 22/9$ and $\lambda^+ \le \lambda < \lambda^\#$, or $\delta > 22/9$ and $0 \le \lambda < \lambda^\#$. The profit is $\pi^*_{A(3)} = \dfrac{9\lambda^2\delta^2 - 18\lambda^2\delta + 9\lambda^2 - 12\lambda\delta - 18\delta + 39}{12\lambda - 36\delta - 36\lambda\delta + 76}$.

Comparing all possible solutions from *Scenario 1* and *2 in (2) and combining them with the results of (1)*, we have the subgame equilibrium of Case 2, in which a proprietary firm competes with an open source firm. The results can be summarized as following:

1) If $1/(\delta - 1) < \lambda \le 1$, the equilibrium results are $p^*_A \ge 0$, $p^*_B = 0$, $N^*_A = 0$, $N^*_B = 1$, $r^*_A = 0$, $r^*_B = \tilde{r}^*_B = 1$, $n^*_A = 0$, $n^*_B = \tilde{n}^*_B = 1/2$, and $\pi^*_A = \pi^*_B = 1/2$.

2) If $2 \le \delta \le 25/9$ and $0 \le \lambda < 1/(\delta - 1)$, or $\delta > 25/9$ and $\lambda_2 \le \lambda < 1/(\delta - 1)$, the equilibrium results are $p^*_A = 1 - \lambda(\delta - 1)$, $p^*_B = 0$, $N^*_A = 0$, $N^*_B = 1$, $r^*_A = 0$, $r^*_B = \tilde{r}^*_B = 1$, $n^*_A = 0$, $n^*_B = \tilde{n}^*_B = 1/2$, and $\pi^*_A = \pi^*_B = 1/2$, where $\lambda_2 = \dfrac{9\delta - 25}{9\delta^2 - 22\delta + 17}$.

3) If $\delta > 25/9$ and $0 \le \lambda \le \lambda_2$, the equilibrium results are $p^*_A = p^*_B = 0$,

$N^*_A = n^*_A = \dfrac{3(\lambda\delta - \lambda - 1)}{3\lambda\delta - \lambda - 6}$, $N^*_B = \dfrac{2\lambda - 3}{3\lambda\delta - \lambda - 6}$, $r^*_A = \dfrac{3(\lambda\delta - \lambda - 1)(\delta - 1)}{3\lambda\delta - \lambda - 6}$, $r^*_B = \dfrac{\lambda + \lambda\delta - 4}{3\lambda\delta - \lambda - 6}$,

$$\tilde{r}_B^* = \frac{3\lambda - \lambda\delta - 2}{3\lambda\delta - \lambda - 6}, \quad n_B^* = \frac{\lambda + \lambda\delta - 4}{2(3\lambda\delta - \lambda - 6)}, \quad \tilde{n}_B^* = \frac{3\lambda - \lambda\delta - 2}{2(3\lambda\delta - \lambda - 6)},$$

$$\pi_A^* = \frac{18\lambda^2\delta^3 - 53\lambda^2\delta^2 + 48\lambda^2\delta - 9\lambda^2 - 36\lambda\delta^2 + 76\lambda\delta - 48\lambda + 18\delta - 14}{2(3\lambda\delta - \lambda - 6)^2}, \text{ and } \pi_B^* = \frac{(\lambda + \lambda\delta - 4)^2}{2(3\lambda\delta - \lambda - 6)^2}.$$

Comparing Firm A's profit with the profit of in Case 1, $(\delta - 1)/4$, we obtain that:

1) If $2 \le \delta \le 25/9$ and $0 \le \lambda \le 1$, or $25/9 < \delta < 3$ and $\lambda_2 \le \lambda < 1$, we have $\pi_A^* = 1/2 > (\delta - 1)/4$.

2) If $25/9 < \delta < 3$ and $0 \le \lambda \le \lambda_2$, or $\delta > 3$ and $0 \le \lambda \le \lambda_1$, we have

$$\pi_A^* = \frac{18\lambda^2\delta^3 - 53\lambda^2\delta^2 + 48\lambda^2\delta - 9\lambda^2 - 36\lambda\delta^2 + 76\lambda\delta - 48\lambda + 18\delta - 14}{2(3\lambda\delta - \lambda - 6)^2} > \frac{(\delta - 1)}{4}, \text{ where}$$

$$\lambda_1 = \frac{18\delta^2 - 52\delta + (10 - 6\delta)\sqrt{(\delta - 1)(9\delta - 19)} + 42}{27\delta^3 - 91\delta^2 + 89\delta - 17} \text{ and } \lambda_1 < \lambda_2.$$

Proof of Proposition 3

Table 2 indicates that the equilibrium depends on the value of C. We denote that for $\delta > 25/9$ and $0 \le \lambda \le \lambda_2$, $C_1 = \frac{18(\delta - 1)(1 + \lambda - \lambda\delta)^2 + (2 + \lambda\delta)^2}{2[6 + (4 - 3\delta)\lambda]^2} - \frac{5}{18}$ and $C_2 = \frac{\delta - 3}{4} - \frac{(2\lambda + 4 - \lambda\delta)^2}{2(4\lambda + 6 - 3\lambda\delta)^2}$.

We can verify that $(\delta - 3)/4 \le 2/9 \le C_1 \le C_2$. The possible equilibria of the game are as follow:

(1) For the development cost satisfying $0 \le C \le \max\{0, (\delta - 3)/4\}$, we have identical equilibria as the case without development cost.

(2) For the development cost satisfying $\max\{0, (\delta - 3)/4\} < C \le 2/9$, we have two possible equilibria: mixed equilibrium when $2 \le \delta \le 25/9$ or $\lambda_2 \le \lambda \le 1$ and proprietary equilibrium

when $25/9 < \delta \leq 35/9$ or $0 \leq \lambda \leq \lambda_2$.

(3) For the development cost satisfying $2/9 < C \leq C_1$, we have two possible equilibria: open source equilibrium when $2 \leq \delta \leq 25/9$ or $\lambda_2 \leq \lambda \leq 1$ and proprietary equilibrium when $25/9 < \delta \leq 35/9$ or $0 \leq \lambda \leq \lambda_2$.

(4) For the development cost satisfying $C_1 < C \leq C_2$, we have two possible equilibria: open source equilibrium always exists and proprietary equilibrium exists when $25/9 < \delta \leq 35/9$ or $0 \leq \lambda \leq \lambda_2$.

(5) For the development cost satisfying $C > C_2$, only open source equilibrium exists.

The total industry profit under the open source equilibrium is $\Pi_O^* = 5/9$, and $\Pi_O^* < \Pi_M^*$ holds for $C < 4/9$. The social welfare under the open source equilibrium is $W_O^* = \beta + 11/36 + \lambda(\delta/2 - 31/36)$, and $W_O^* < W_M^*$ holds for $C < 7/36 + \lambda(\delta/2 - 7/18)$. We can verify $7/36 + \lambda(\delta/2 - 7/18) \geq 2/9$ as long as λ is not too small.

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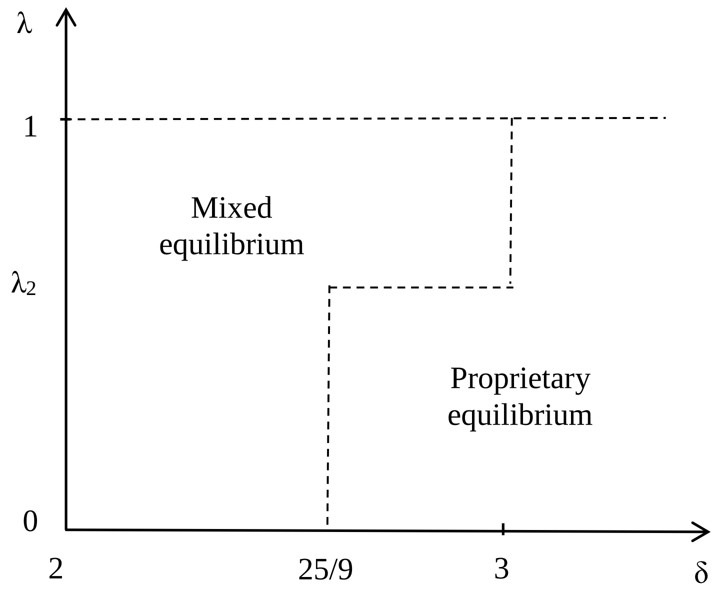
[Table 1] Payoffs under different system development strategies

		Firm *B*	
		Proprietary	Open source
Firm *A*	Proprietary	$(\delta - 1)/4$, $(\delta - 1)/4$	π_1, π_2
	Open source	π_2, π_1	5/18, 5/18

where $\pi_1 = \pi_2 = 1/2$ for $2 \leq \delta < 25/9$ or $\lambda_2 < \lambda \leq 1$, with $\lambda_2 = \dfrac{9\delta - 25}{9\delta^2 - 22\delta + 17}$, and for otherwise

$$\pi_1 = \frac{18\lambda^2\delta^3 - 53\lambda^2\delta^2 + 48\lambda^2\delta - 9\lambda^2 - 36\lambda\delta^2 + 76\lambda\delta - 48\lambda + 18\delta - 14}{2(3\lambda\delta - \lambda - 6)^2} \text{ and } \pi_2 = \frac{(\lambda + \lambda\delta - 4)^2}{2(3\lambda\delta - \lambda - 6)^2}.$$

[Figure 1] Market equilibrium

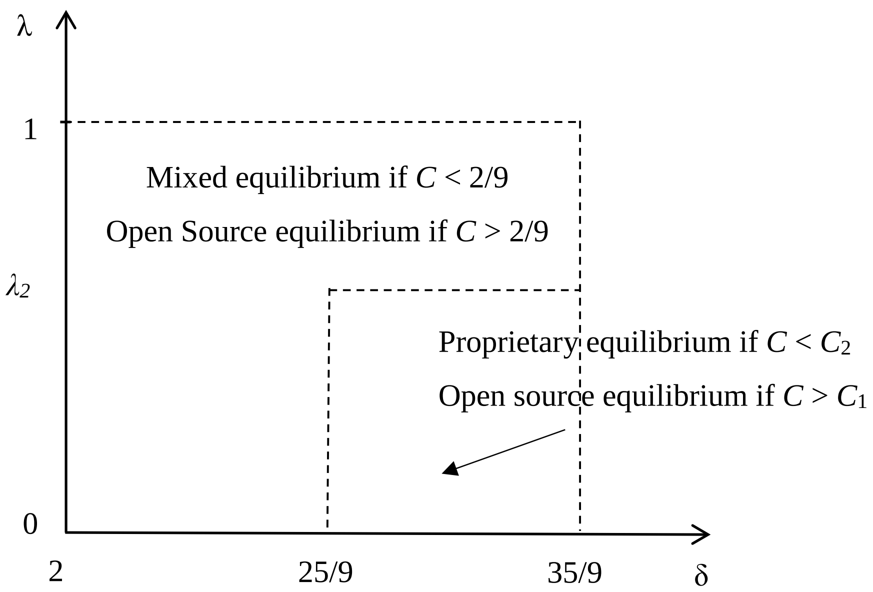


[Table 2] Payoffs with the presence of system development cost

		Firm *B*	
		Proprietary	Open source

Firm *A*	Proprietary	$(\delta - 1)/4 - C$, $(\delta - 1)/4 - C$	$(\pi_1 - C)$, π_2
	Open source	π_2, $(\pi_1 - C)$	5/18, 5/18

[Figure 2] Market equilibrium with system development costs



where $C_1 = \frac{18(\delta-1)(1+\lambda-\lambda\delta)^2 + (2+\lambda\delta)^2}{2\left[6+(4-3\delta)\lambda\right]^2} - \frac{5}{18}$ and $C_2 = \frac{\delta-3}{4} - \frac{(2\lambda+4-\lambda\delta)^2}{2(4\lambda+6-3\lambda\delta)^2}$, with

$2/9 \le C_1 \le C_2$.

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