Research Paper Series

No. 92

Strategic investment in information security of firms: R&D spillovers and information management

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September 2011

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September 15, 2011

Abstract

This paper analyzes interplay between the investments in R&D and in information security of a firm and interaction between the optimal strategies of the firms in a competitive market structure. For this purpose, we propose the two-stage Cournot duopoly model, where firms choose investment in information security to prevent the knowledge spills over to its rival simultaneously with the R&D investment in the first stage and compete in the product market in the second stage. We find that the optimal strategies of firms to prevent information leakage through information security investment and that an interior Nash equilibrium exists in this model. Further we show that the investment in information security of firms are strategic substitutes and are complementary to the investment in R&D. The firms not only reduce their involuntary spillovers but also increase net profit through investment in information security in a competitive market.

1 Introduction

Many firms are investing in information-security technologies and processes to reduce the likelihood of information leakage. For example, data encryption, firewalls, anti-virus software, patching software, access control systems, and security personnel are common. The information security reduces diffusion of the confidential information of the firm and prevents copying technologies by rivals. The information security, however, has no effect on process or product innovation of the firm, or even worse, its costs reduce the net profit of the firm. Is there any reason why the information security is important for the firms? Thus, we consider an optimal strategy of information security of firms in a competitive market.

*I would like to thank Takahiro Watanabe, Ken-ichi Tatsumi, Shinsuke Kambe, Daisuke Shimizu, and Jun Wako for their helpful comments on an earlier version of this paper. Of course, any remaining errors are my responsibility.

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It is very difficult to keep anything secrets in the present information age when the Internet has led to trends in globalization and has reduced the cost of information sharing. A number of firms, as information producers, enjoy monopolies and post-innovation profits from their confidential information. The information is classified as an intangible asset, such as R&D efforts, trade secrets, knowledge, or information assets, which firms have a strategic incentive to protect from others, especially rival firms. On the other hand, firms have incentives to coordinate the research joint ventures (RJVs) that reduce the cost of R&D and speed innovation.

The optimal level of the investment in information security and R&D are of interest to the firms. Firms have a strong desire to manage their information or knowledge, disclosing some information and preventing the involuntary spillover of confidential information. Firms form an RJV to share information, e.g., new technologies and market conditions. Not surprisingly, however, a firm that achieves a significant process innovation will not be willing to share its information with rival firms. For example, Intel never advises rivals as to how to reduce the production cost of new CPUs (Central Processing Units). Hence, if the firms manage to reduce the spillover through investment in information security, they might opt to retain control of the spillover. At least, the firms will reduce the involuntary spillover through information-security investment.

In this paper, we develop a two-stage duopoly model in which we solve the optimal strategy for the investment in the information security of firm in the competitive market and Nash equilibrium. Two firms simultaneously choose two variables, the level of R&D and of information security in the first stage, and the firms engage in a Cournot quantity competition in the second stage. The proposed model also allows us to demonstrate that the spillover of a firm is endogenized by the information-security investment of the firm.

We investigate the following: (1) In the equilibrium, by investing in information security, the firm increases its net profit that stems from the strategic effect of information security. (2) In our model, there exists an interior Nash equilibrium but this equilibrium is not Pareto efficient. (3) The information-security investments of firms are strategic substitutes. (4) Information-security investment acts as a gross-complement for R&D investment, whereas R&D investment acts as a gross-substitute for information security.

A number of researchers have reported that information security is not only a technological problem but also an economic problem. In his seminal work, Anderson (2001) argued that perverse incentives to create insecure systems have caused as much harm as technological defects. Varian (2000) stated that when groups have different incentives, information and systems cannot be secured, even when protected by high-tech encryption systems. A survey by Anderson and Moore (2006) investigated the economics of information security.

Gordon and Loeb (2002) used a cost-benefit analysis to determine the optimal level of investment in information security by a firm. They compared the cost of information security with the expected benefit obtained through these efforts. This seminal model has been expanded by Hausken (2006) and Willemson (2006).

Most of these studies have investigated the optimal investment in information security of firms in a non-competitive environment. We, however, consider the optimal level of information-security investment of firms in a competitive market, because most firms operate in a competitive industry or market.

In this study, we focus on the firms that investments in R&D for process innovation and information security to protect their R&D efforts. R&D efforts are classified into two types, process innovation and product innovation. Often, however, it has been argued that, from a logical point of view, there is no difference between these two types of innovation.[1] In addition we do not address information protected by laws, such as patent protection, because this information is not private, but rather public. Therefore, firms have no reason to spend money on information security to protect this information.

Accordingly, the players in the model of this study are two firms that are searching for cost-reducing technologies in a duopoly market. In addition, these firms protect the results of their own process innovation from their rivals, not through legal restrictions such as patents, copyrights, and licenses, but through information security.

Theoretically, researches in R&D and information spillover have been conducted to examine the economics of RJVs. In their seminal research, Katz (1986), d'Aspremont and Jacquemin (1988), Suzumura (1992), and Kamien et al. (1992), for example, provided seminal analysis and models[2]. These studies revealed that if the spillover is significantly large, then the cartelized RJV is superior to other scenarios with respect to the firms earnings and social welfare.[3]

These seminal models of RJV studies have been extended and expanded in various directions. In particular, Kultti and Takalo (1998), Katsoulacos and Ulph (1998), Poyago-Theotoky (1999), Kamien and Zang (2000) and Gersbach and Schmutzler (2003) expanded the model proposed in d'Aspremont and Jacquemin (1988) to a three-stage model and endogenized spillovers. Grunfeld (2003) developed a model where spillovers were endogenized as a absorptive capacity with two-stage model.

In this paper, we expand the model proposed by d'Aspremont and Jacquemin (1988), henceforth DJ, with the effectiveness of the information-security investment, which decreases *involuntary spillovers* and impedes the cost-reduction of rival firms by the spillover. The effect of decreasing the cost-reduction of the rival firm by spillovers, or the information-security level, is denoted by Z_i, and the involuntary spillover coefficient is denoted as $\alpha \in [0, 1]$.

The paper is organized as follows. In Section 2, we construct a two-stage model for information-security investment. In Section 3, we analyze the symmetric best response strategy of a firm and demonstrate the existence of an interior Nash equilibrium of the model. In Section 4, we investigate the general SPNE strategy of a firm under conditions in which firms wish to protect their confidential information. Concluding remarks are presented in Section 5.

[1] See, Shy (1996).
[2] See Amir (2000) for a critique of these models.
[3] See De Bondt (1996) for a survey of this research.

2 The model

2.1 Two-stage model for information-security investment

Consider an industry with two firms, denoted as firms i and j, which produce identical products. In the first stage, the R&D stage, each firm simultaneously decides two amounts of investment in cost-reduction R&D and information security. In the second stage, the market competition stage, the firms engage in Cournot quantity competition. The objective of each firm is to maximize net profit by deciding the optimal level of R&D and information security.

Information-security investment reduces spillover and impedes the cost-reduction of the rival. The R&D activities of the firms create confidential information that decrease the firm's production cost during the market competition stage. In addition, the confidential information created by each firm also reduce the production cost of the rival firm by spillover. For example, a cell phone can be decomposed into two components, namely, the electronic circuit board and the case. Firm i obtains the cost reduction technology for the electronic circuit board, and firm j obtains the cost reduction technology for the case. Each firm can use the technology developed by the other firm without cost.

Suppose that Q and $P(Q)$ are the total quantity and the price in the market, respectively. Let a be a positive constant. The inverse demand function is given by $P(Q) = a - Q$. Denoting the production quantity of firm i by q_i, we have $Q = q_i + q_j$, where $j \neq i$. Let c_i be the production cost of firm i in the market competition stage and let q_i^* be the equilibrium output of firm i.

$$q_i^* = \frac{a - 2c_i + c_j}{3}, \quad j \neq i.$$

Thus, the aggregate industry-output level is $Q = (2a - c_i - c_j)/3$. It follows that the Cournot profit level of firm i is given by

$$\begin{aligned} \pi_i^*(q_i^*, q_j^*, c_i) &= P(q_i^* + q_j^*)q_i^* - c_i q_i^* \\ &= \frac{1}{9}(a - 2c_i + c_j)^2, \quad j \neq i. \end{aligned}$$

Let $X_i \geq 0$ be the R&D level. The R&D level is the amount of cost reduction achieved through the R&D undertaken by firm i. Let $Z_i \geq 0$ be the information-security level. The information-security level is the amount of the decrease in the cost-reduction of rival firm j achieved through the information-security investment of firm i to prevent spillovers. The R&D level and the information-security level affect q_i^*, q_j^*, and c_i.

When the firms choose X_i and Z_i in the R&D stage, they have to pay costs of the R&D and information security. Let $C_R(X_i)$ be the cost function of R&D and $C_S(Z_i)$ be the cost function of information security. Suppose that Π_i is the net profit of firm i, we obtain

$$\Pi_i = \pi_i^* - C_R(X_i) - C_S(Z_i).$$

2.2 Information structures and involuntary spillover

Assume that the information of the firms is classified into two broad types: *disclosed information* and *confidential information*. Disclosed information might become public, whereas confidential information should be kept secret. Assuming that the information reduces the production costs of the firms in the market competitive stage, we measure the information in terms of R&D level.

Let $\beta \in [0, 1]$ be the spillover coefficient that indicates the rate of the disclosed information. Consequently, the R&D level achieved by the disclosed information is βX_i and the R&D level achieved by the confidential information is $(1 - \beta)X_i$. If the confidential information of firm i also spills over to rival firm j, X_i contributes to the R&D level of firm j. As a result, the effective cost-reduction of firm j is $X_j + X_i$. In this case, however, even if firm i performs no action to secure its confidential information, all of the confidential information of firm i will not always spillover.

Therefore, we assume that confidential information will be leaked at a rate of $\alpha \in [0, 1]$. Thus, let $\sigma = \alpha(1 - \beta)$ be the rate of involuntary spillovers and let $\rho = 1 - \beta - \alpha(1 - \beta) = (1 - \alpha)(1 - \beta)$ be the rate of information that has been kept secret from rival firms. In other words, ρX_i is the R&D level by exclusively usable information. Therefore, the effective R&D level of firm j with the involuntary spillover of firm i is given by $X_j + (\beta + \sigma)X_i$.

Figure 1 shows the information that has obtained through R&D efforts of a firm as the three rectangle regions, D, R, and S plotted on the $[0, 1]^2$ plane. First, the area of rectangular region D, $1 \times \beta$, shows the disclosed R&D information. Second, the area of region S, σ, corresponds to the involuntary spillover. Third, the area of region R, ρ, depicts the information that the firm exclusively uses its R&D efforts.

We now use the simple information-framework above to explain the information-security investment and the strategy of the firm.

2.3 Investment in information security

Let $Z_i \leq X_1$ be the information-security level of firm i. Thus, σZ_i is the actual effect of the information-security investment. In contrast, the information-security investment of rival firm j reduces the involuntary spillover of firm j. Therefore, the effective R&D level of firm i with the information-security investment is given by $X_i + (\beta + \sigma)X_j - \sigma Z_j$. If there is no involuntary spillover from firm j, i.e., $\sigma = 0$, then the effectiveness of the information-security level is 0. By investing in information security, a firm is able to reduce involuntary spillover as well as the effective R&D level of the rival firm.

Figure 2 illustrates X_i and Z_i graphically. The rectangular prism, $1 \times 1 \times X_i$, shows the R&D level obtained through the R&D efforts of firm i, and σX_i shows the R&D level obtained through the involuntary spillover of firm i. If firm i invests in information security to reduce the amount of spillover σZ_i. Thus, the information-security investment of firm i affects the cost reduction of firm j, which is denoted as $(\beta + \sigma)X_i - \sigma Z_i = (1 - \rho)X_i - \sigma Z_i$.

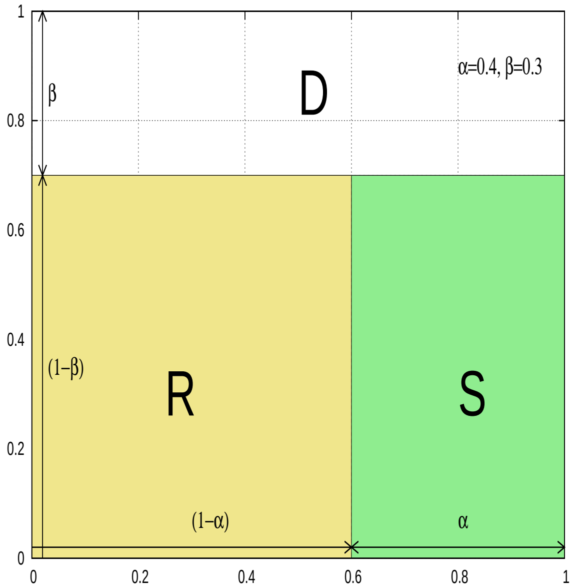

Figure 1: Area of region $R: \ \rho = (1-\alpha)(1-\beta)$ indicates the exclusively usable R&D efforts without spillovers. The area of region $D: \ 1 \times \beta$ is the spillover effect adopted disclosed information. The area of region $S: \sigma = \alpha(1-\beta)$ indicates the involuntary spillover. These results are for the case in which $\alpha = 0.4, \beta = 0.3$.

2.4 Cost reduction effects in the market competition stage

Let c_i be the marginal production cost of each firm in the market competition stage. Suppose $\bar{c}$ is the marginal production cost of the firm in the R&D stage, we have

$$c_i(X_i, X_j, Z_j) = \\ \bar{c} - X_i - (1-\rho)X_j + \sigma Z_j, \ j \neq i \ . \quad (1)$$

Assumption 1. *The R&D level does not exceed the production cost during the R&D stage, i.e.,* $\bar{c} - X_i - (1-\rho)X_j > 0$.

When the involuntary spillover, α, is zero, this cost schedule is same as that of the DJ model. It follows that, the output level of each firm in Cournot equilibrium is given

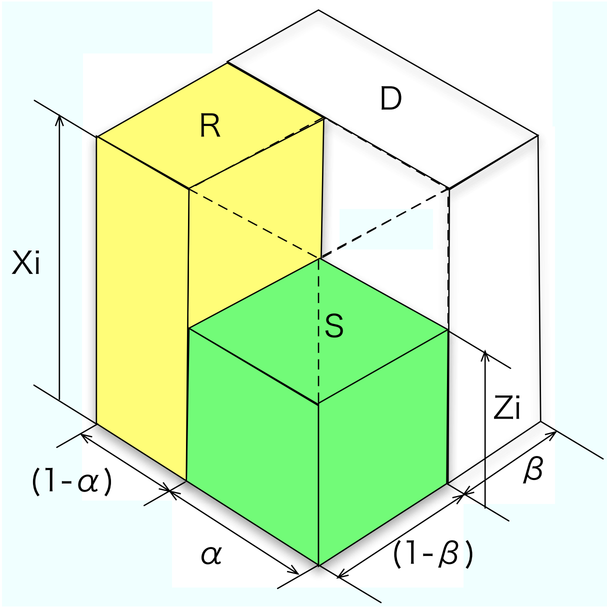

Figure 2: R&D investment and effectiveness of information-security investment in three-dimensional space for the case in which $Z_i < X_i$. The rectangular solid, $1 \times 1 \times X_i$, indicates the effective cost reduction through the R&D efforts of firm i. The rectangular prism $\sigma X_i = \alpha(1-\beta)X_i$ indicates the involuntary spillover, and the rectangular prism σZ_i indicates the effective prevention of involuntary spillover through investment in information security.

by

$$\begin{aligned}
q_i^* =& \frac{1}{3}[a - 2c_i(X_i, X_j, Z_j) + c_j(X_i, X_j, Z_j)] \\
=& \frac{1}{3}[a - 2(\bar{c} - X_i - (1-\rho)X_j + \sigma Z_j) + \\
& (\bar{c} - X_j - (1-\rho)X_i + \sigma Z_i)] \\
=& \frac{1}{3}\{a - \bar{c} + 2\,[X_i + (1-\rho)X_j - \sigma\, Z_j] - \\
& [X_j + (1-\rho)X_i - \sigma\, Z_i]\} \\
=& \frac{1}{3}\,[a - \bar{c} + (1+\rho)X_i + (1-2\rho)X_j + \sigma Z_i - 2\sigma Z_j]\,.
\end{aligned}$$

Hence, the aggregated industry-output level is

$$\begin{aligned}
Q^* &= \frac{1}{3}[2a - c_i(X_i, X_j, Z_j) - c_j(X_i, X_j, Z_j)] \\
&= \frac{1}{3}[2a - 2\bar{c} + (2-\rho)(X_i + X_j) - \sigma(Z_i + Z_j)].
\end{aligned}$$

Therefore, the equilibrium price is

$$\begin{aligned}
p^* &= a - (q_i^* + q_j^*) \\
&= a - Q^* \\
&= \frac{1}{3}[a + 2\bar{c} - (2-\rho)(X_i + X_j) + \sigma(Z_i + Z_j)].
\end{aligned}$$

It follows that a gross profit of firm i is given by

$$\begin{aligned}
\pi_i^* &= (p^* - c_i)q_i^* = (q_i^*)^2 \\
&= \frac{1}{9}\left\{a - \bar{c} + 2\left[X_i + (1-\rho)X_j - \sigma\, Z_j\right] - \right. \\
&\quad \left.\left[X_j + (1-\rho)X_i - \sigma\, Z_i\right]\right\}^2 \\
&= \frac{1}{9}\left[a - \bar{c} + (1+\rho)X_i + (1-2\rho)X_j + \sigma Z_i - 2\sigma Z_j\right]^2.
\end{aligned}$$

Finally, we apply the following quadratic cost function for the investment in R&D and in information security, and the shift parameters of these cost functions are γ and κ.

$$\begin{aligned}
C_R(X_i) &= \frac{\gamma}{2}{X_i}^2, \ \gamma > 0, \\
C_S(Z_i) &= \frac{\kappa}{2}{Z_i}^2, \ \kappa > 0.
\end{aligned}$$

Next, we expand $C_R(X_i)$ and $C_S(Z_i)$. Then, the net profit level of firm i, $\Pi_i(X_i, Z_i, X_j, Z_j)$, is given by

$$\begin{aligned}
\Pi_i &= \pi_i^*(q_i^*, q_j^*, c_i) - C_R(X_i) - C_S(Z_i) \\
&= \frac{1}{9}\left\{a - \bar{c} + 2\left[X_i + (1-\rho)X_j - \sigma\, Z_j\right] - \left[X_j + (1-\rho)X_i - \sigma\, Z_i\right]\right\}^2 - \\
&\quad \frac{\gamma}{2}{X_i}^2 - \frac{\kappa}{2}{Z_i}^2 \\
&= \frac{1}{9}\left[a - \bar{c} + (1+\rho)X_i + (1-2\rho)X_j - 2\sigma Z_j + \sigma Z_i\right]^2 - \\
&\quad \frac{\gamma}{2}{X_i}^2 - \frac{\kappa}{2}{Z_i}^2. \qquad (2)
\end{aligned}$$

Assumption 2. *Demand is sufficiently high relative to cost, so that* $a > \bar{c} + \sigma Z_i$.

See Figure 3, which illustrates the timing of this model.

3 The best response functions

In this section, we examine that an existence of a symmetric interior equilibrium in this model and the best response functions of the firms.

R&D stage | market competition stage

R&D investment $\frac{\gamma}{2}{X_i}^2$
information-security investment $\frac{\kappa}{2}{Z_i}^2$
initial production cost $\bar{c}$

Cournot market
production cost $c_i = \bar{c} - X_i - (1-\rho)X_j + \sigma Z_j$
quantity $q_i = \frac{1}{3}(a - 2c_i + c_j)$
gross profit $\pi_i^* = \frac{1}{9}(a - 2c_i + c_j)^2$
net profit $\Pi_i = \pi_i^* - \frac{\gamma}{2}{X_i}^2 - \frac{\kappa}{2}{Z_i}^2$

Figure 3: Timing of the two-stage model for information-security investment. $i \neq j$.

3.1 Existence of interior equilibrium

We assume that the strategies of firm i are positive, $X_i > 0$ and $Z_i > 0$. Hence, the following assumptions confirm the existence of an interior equilibrium. See Appendix.

Assumption 3.

1. $\gamma > \begin{cases} \dfrac{2}{9}(2-\rho)(1+\rho) & \text{if } \rho < \dfrac{1}{2} \\ \dfrac{2}{9}(1+\rho)^2 & \text{if } \rho \geq \dfrac{1}{2}. \end{cases}$
2. $\gamma > \dfrac{2\kappa(1+\rho)^2}{9\kappa - 2\sigma^2}$.
3. $\kappa > \dfrac{2}{9}\sigma^2$.

3.2 Best-response functions

Each firm selects the best-response strategy for R&D in order to maximize its net profit. The first-order condition for profit maximization that the net profit Π_i of firm i with respect to Z_i yields

$$\frac{\partial \Pi_i}{\partial Z_i} = \frac{2}{9}\sigma\,[a - \bar{c} + (1+\rho)X_i + (1-2\rho)X_j + \sigma\,(Z_i - 2\,Z_j)] - \kappa Z_i = 0.$$

Hence, the best-response function of information-security level $\hat{Z}_i$ is given by

$$\hat{Z}_i = \frac{\frac{2}{9}\sigma}{\kappa - \frac{2}{9}\sigma^2}\,[a - \bar{c} + (1+\rho)X_i + (1-2\rho)X_j - 2\,\sigma Z_j]\,. \tag{3}$$

Similarly we have,

$$\frac{\partial \Pi_i}{\partial X_i} = \frac{2}{9}\,(1+\rho)\,[a - \bar{c} + (1+\rho)X_i + (1-2\rho)X_j + \sigma(Z_i - 2Z_j)] - \gamma X_i = 0.$$

Hence, the best-response of R&D level $\hat{X}_i$ is given by

$$\hat{X}_i = \frac{\frac{2}{9}(1+\rho)}{\gamma - \frac{2}{9}(1+\rho)^2}\left[a - \bar{c} + (1-2\rho)X_j + \sigma(Z_i - 2Z_j)\right].$$

The best-response function (3) implies that when the R&D level of firm i and the information-security level of firm j are give, if a rate of R&D effort that exclusively usable by the firm is higher than 1/2, then the information-security level increases with a decrease in the R&D level of rival firm. Formally, if $\rho > 1/2$, then $\hat{Z}_i$ increases with a decrease in X_j. Hence, if the spillover is smaller than 1/2, then the optimal information-security level of the firm increases with a decrease of R&D level of the rival firm.

In addition, we have cross partial derivative of profit with respect to the decision of each firm,

$$\frac{\partial^2 \Pi_i}{\partial Z_i \, \partial Z_j} = -\frac{4}{9}\sigma^2 < 0.$$

Therefore, we have the following proposition:

Proposition 1. *The information-security levels of the two firms, Z_i and Z_j, are strategic substitutes.*

4 Strategies for information-security investment

In this section, we analyze the optimum strategy of information-security investment for the symmetric duopoly market and obtain the equilibrium.

4.1 Symmetric Nash equilibrium

Given $Z_i = Z_j = Z$ and $X_i = X_j = X$. The symmetric best-response function $\hat{Z}^c$ are obtained by solving $\max_Z \Pi_i(X, Z)$. Since the first-order conditions of profit maximization can be written as $\frac{\partial \Pi_i}{\partial Z}(X, Z) = 0$, we have

$$0 = \frac{2}{9}\sigma\left[a - \bar{c} + (2-\rho)X\right] - (\kappa + \frac{2}{9}\sigma^2)Z.$$

Thus, the best-response strategy for information security in the symmetric market is given by

$$\hat{Z}^c = \frac{2\,\sigma\,\left[a - \bar{c} + (2-\rho)X\right]}{9\,\kappa + 2\,\sigma^2} \tag{4}$$

and $\hat{Z}^c$ is positive.

Similarly, let $\hat{X}^c$ be the best-response strategy for R&D of firm i, which solves $\max_X \Pi_i(X, Z)$. Since the first-order conditions of profit maximization can be written as $\frac{\partial \Pi_i}{\partial X}(X, Z) = 0$, we have

$$0 \;=\; \frac{2}{9} - 2\,(1+\rho)\;[a - \bar{c} + (2-\rho)X - \sigma\, Z] - \gamma\, X.$$

Hence,

$$\hat{X}^c \;=\; \frac{2(a - \bar{c} - \sigma\, Z)(1+\rho)}{9\gamma - 2(2-\rho)(1+\rho)}. \tag{5}$$

Differentiating (4) and (5) with respect to X and Z, we obtain

$$\begin{aligned} \frac{\partial \hat{Z}^c}{\partial X} &= \frac{2\,\sigma\,(2-\rho)}{9\kappa + 2\,\sigma^2} > 0. \\ \frac{\partial \hat{X}^c}{\partial Z} &= -\frac{2\,\sigma\,\;(1+\rho)}{9\,\gamma - 2\;(2-\rho)\;(1+\rho)} < 0. \end{aligned} \tag{6}$$

Equation (6) is negative, because of $2\sigma(1+\rho) > 0$ and $9\gamma - 2(2-\rho)(1+\rho) > 0$ by Assumption 3. Hence, we have

Proposition 2. *In the symmetric duopoly market,*

1. *The best-response strategy of information-security level increases with an increase in R&D level. Formally, Z^c increases with an increase in X^c.*

2. *The best-response function of R&D level increases with a decrease in the information-security level. Formally, X^c increases with a decrease in Z^c.*

The intuition behind Proposition 2 is as follows. If the firm increases the R&D level, the firm should also increase the information-security level. On the other hand, the firm increases information-security level, the firm decreases the R&D level. Therefore, firms have another way to increase their net profit, namely, information-security investment.

By investing in information security, the firm increases its net profit that stems from the strategic effect of information security. Although the information security reduces the net profit of the firm by its cost and does not reduce the marginal production cost of firm, the information security affects the action of rival firm. As a result, the action of the rival firm that reduces the quantity of product causes the increase of the net profit level of the firm investing in information security.

Consequently, when each firm decides to invest in information security in order to increase the net profit, each rival firm invests in information security as the best response to the strategy of the rival. As a result, the firms reach a Nash equilibrium in R&D and information-security levels. However, the more each firm increases its information-security investment in order to increase its own profit, the greater the reduction in the total social welfare. It follows that, the situation is similar to the prisoner's dilemma; in other word, the Nash equilibrium is not Pareto efficient from the viewpoints of maximization of the profit of the firm and social welfare.

Theoretically, if the usable information that stems from the R&D efforts is shared within RJV firms, the profit of the firms and the social welfare are maximized, according to the literature on RJVs. Each firm, however, has an incentive to hide the confidential information obtained through R&D efforts to maximize profits and decides to invest in information security as a result of the best response to the strategy of its rival. Consequently, their actions converge to a Nash equilibrium.

Although from the viewpoint of social welfare, firms should not invest in information security, this is not a practical option in this model. There is an interior Nash equilibrium, which causes *rational* players to decide to invest in information security in a competitive market environment. Summarizing this discussion, we have the following theorem:

Theorem 1. *The Nash equilibrium in information-security investment is not Pareto efficient.*

By (4) and (5), substituting Z^c and X^c for one another, we have symmetric Nash equilibrium

$$Z^* = \frac{2(a-\bar{c})\sigma}{\kappa\,[9\gamma - 2(2-\rho)(1+\rho)] + 2\,\gamma\,\sigma^2}, \tag{7}$$

$$X^* = \frac{2(a-\bar{c})(1+\rho)}{\kappa\,[9\gamma - 2(2-\rho)(1+\rho)] + 2\,\gamma\,\sigma^2}. \tag{8}$$

Comparing (7) with (8) yields

Proposition 3. *In the symmetric equilibrium, optimal information-security level and R&D level satisfy*

$$Z^* = \frac{\sigma}{1+\rho} X^*$$

The intuition behind Proposition 3 is that when the involuntary spillover increases, the firm will increase information-security level. On the other hand, when the information exclusively usable increases, the firm will decrease information-security level.

4.2 Comparative statics

We show the characteristics of information-security and R&D investment with comparative statics by shift parameters, α, β, λ and κ. First, we note that Z^* and X^* are altered by the parameters, the coefficient of involuntary spillover α, and the coefficient of the spillover by disclosed information β.

$$\frac{\partial Z^*}{\partial \alpha} > 0 \tag{9}$$
$$\frac{\partial Z^*}{\partial \beta} < 0 \tag{10}$$
$$\frac{\partial X^*}{\partial \alpha} < 0. \tag{11}$$

We consider these two cases to analyze an effect of β on X^*.

$$\begin{aligned} &\text{Case 1.} \quad \kappa < \frac{2(1+\rho)}{9\gamma} + \frac{4\alpha^2(1-\beta)}{9(1-\alpha)} + \frac{2}{9}\sigma^2. \text{ Then} \\ &\qquad\qquad \frac{\partial X^*}{\partial \beta} > 0. \\ &\text{Case 2.} \quad \kappa > \frac{2(1+\rho)}{9\gamma} + \frac{4\alpha^2(1-\beta)}{9(1-\alpha)} + \frac{2}{9}\sigma^2. \text{ Then} \\ &\qquad\qquad \frac{\partial X^*}{\partial \beta} < 0. \end{aligned} \tag{12}$$

Proof: See Appendix.

Second, Z^* and X^* are altered by the shift parameters γ and κ, which are the cost parameters for the investments.

$$\frac{\partial Z^*}{\partial \gamma} < 0 \tag{13}$$
$$\frac{\partial Z^*}{\partial \kappa} < 0 \tag{14}$$
$$\frac{\partial X^*}{\partial \gamma} < 0 \tag{15}$$
$$\frac{\partial X^*}{\partial \kappa} > 0. \tag{16}$$

Proof: See Appendix.

Therefore, we can state the following proposition:

Proposition 4. *In equilibrium,*

1. *the information-security level increases with an increase in the rate of involuntary spillover and with a decrease in the rate of disclosed information. Formally, Z^* increases with an increase in α and with a decrease in β.*

2. *the R&D level increases with*

   (a) *a decrease in the rate of involuntary spillover. Formally, X^* increases with a decrease in α.*

   (b) *an increase in the rate of disclosed information if and only if the price of investment in information security is lower than $\frac{2(1+\rho)}{9\gamma}+\frac{4\alpha^2(1-\beta)}{9(1-\alpha)}+\frac{2}{9}\sigma^2$. Formally, X^* increases with an increase in β if and only if $\kappa<\frac{2(1+\rho)}{9\gamma}+\frac{4\alpha^2(1-\beta)}{9(1-\alpha)}+\frac{2}{9}\sigma^2$.*

   (c) *a decrease in the rate of disclosed information if and only if the price of investment in information security higher than $\frac{2(1+\rho)}{9\gamma}+\frac{4\alpha^2(1-\beta)}{9(1-\alpha)}+\frac{2}{9}\sigma^2$. Formally, X^* increases with a decrease in β if and only if $\kappa>\frac{2(1+\rho)}{9\gamma}+\frac{4\alpha^2(1-\beta)}{9(1-\alpha)}+\frac{2}{9}\sigma^2$.*

3. *the information-security level increases with a decrease in the price of investment in R&D and information security. Formally, Z^* increases with a decrease in λ and κ.*

4. *the R&D level increases with a decrease in the price of investment in R&D and with an increase in the price of information security. Formally, X^* increases with a decrease in λ and with an increase in κ.*

Parts 1 and 2a of Proposition 4 state that when the rate of involuntary spillover increases, the firm will raise the information-security level and reduce the R&D level. Indeed, an increase in the rate of disclosed information will reduce the information-security level of the firm. The intuition behind parts 2b and 2c of the proposition is as follows. When the price of R&D investment is too high, the level of R&D increases with a decrease in the rate of disclosed information. In contrast, when the price of R&D is not expensive, the level of R&D increases with an increase in the rate of disclosed information. The concept behind parts 3 and 4 of the proposition is as follows. The cross-price effect of the level of information security and the price of R&D acts as a gross-complement, whereas that of the level of R&D and the price of information security acts as a gross-substitute.

5 Conclusion

In the present paper, we examined the optimal information-security investment of firms that spend significant amounts on R&D in a two-stage duopoly Cournot competitive industry. We found the following. By investing in information security, a firm increases its net profit level with the strategic effect in the equilibrium. There exists an internal Nash equilibrium in this model. This equilibrium, however, is not Pareto efficient. In addition to when the involuntary spillover of firm increases, the net profit of firm will decrease and therefore the firm will increase the level of information security. Also, information-security investment acts as a gross-complement for R&D investment. Thus, when the firm increases its information-security level, the firm will decreases its R&D level.

As long as usable information or knowledge is protected, social welfare will not be maximized. The firms, however, have incentives to secret their confidential information obtained through R&D efforts in order to enjoy monopolistic profit. Moreover, it is difficult for firms to deviate from the equilibrium without information-security investment.

The firms can enter into contracts with each other in order to cooperate in R&D efforts through the RJV, which is one solution to this problem. Nevertheless, there are theoretical and practical problems associated with such contracts. Indeed, the members of the RJV will have an incentive for exclusive use of the confidential information obtained through the RJV.

In the present paper, we focus on a symmetric duopoly model. There are several directions in which to extend our analysis. Equilibrium outcomes in an asymmetric duopoly remain for future research. Moreover, simply expanding an n-firm oligopoly model would not be difficult. Furthermore, if three firms enter into contracts with each other, this is another perspective on the firm's information management game. In terms of the information management of firms, privacy is an important and difficult problem.

APPENDIX

A.1 Proof of existence of equilibrium

Proof. We solve conditions for the existence of an equilibrium. In order to ensure the existence of the equilibrium, it is sufficient to satisfy the following conditions:

$$\frac{\partial^2 \Pi_i}{\partial Z_i^2} < 0 \tag{17}$$

and the determinant of Hessian matrix of Π_i, which is denoted by $|H|$, is

$$|H| = \frac{\partial^2 \Pi_i}{\partial X_i^2}\frac{\partial^2 \Pi_i}{\partial Z_i^2} - \left(\frac{\partial^2 \Pi_i}{\partial X_i \partial Z_i}\right)^2 > 0. \tag{18}$$

Statements (17) and (18) imply that $\frac{2}{9}(1+\rho)^2 - \gamma < 0$, $(2\sigma^2 - 9\kappa)\gamma + 2\kappa(1+\rho)^2 > 0$, and $\frac{2}{9}\sigma^2 - \kappa < 0$.

By equation (5), $\hat{X}^c$ is defined as follows:

$$\hat{X}^c = \frac{2(a - \bar{c} - \sigma Z_i)(1+\rho)}{9\gamma - 2(2-\rho)(1+\rho)}.$$

Assume that $\hat{X}^c > 0$, $0 \leq \rho \leq 1$, and $a \geq \bar{c} + Z_i$, then the numerator of the right-hand side (RHS) is positive, because $(1+\rho) \geq 0$ and $a - \bar{c} - Z_i \geq 0$. Therefore, the denominator of the RHS should be positive. Hence,

$$\gamma \;>\; \frac{2}{9}(2-\rho)(1+\rho)$$

□

B Proof of (9) through (12)

Proof. Partial derivative of Z^* with respect to α is

$$\frac{\partial Z^*}{\partial \alpha} = \frac{2(a-\bar{c})(1-\beta)\gamma\left[\kappa\left\{9\gamma - 2(1-\beta)[(1-\alpha^2)\beta - \alpha^2] - 4\right\} - 2\gamma\sigma^2\right]}{\left[\kappa\left\{9\gamma + 2(2-\rho)(1+\rho)\right\} + 2\gamma\sigma^2\right]^2}.$$

Since $\kappa\left\{9\gamma - 2(1-\beta)[(1-\alpha^2)\beta - \alpha^2] - 4\right\} - 2\gamma\sigma^2 > 0$, it follows that $\partial Z^*/\partial\alpha > 0$. We obtain $\gamma(9\kappa - \sigma^2) - 2\kappa\left\{(1-\beta)\left[(1-\alpha^2)\beta - \alpha^2\right] - 2\right\} > 0$, because $\alpha \in [0,1], \beta \in [0,1]$, then $(1-\beta)[(1-\alpha^2)\beta - \alpha^2] - 2 < 0$. Therefore,

$$\frac{\partial Z^*}{\partial \alpha} \;>\; 0.$$

□

Proof. Partial derivative of Z^* with respect to β is

$$\frac{\partial Z^*}{\partial \beta} = -\frac{2(a-\bar{c})\gamma\alpha\left[\gamma(9\kappa - 2\sigma^2) + 2\kappa(1-\rho^2)\right]}{[\gamma(9\kappa - 2\sigma^2) - 2(2-\rho)(1+\rho)\kappa]^2}.$$

Therefore,

$$\frac{\partial Z^*}{\partial \beta} \;<\; 0.$$

□

Proof. Partial derivative of X^* with respect to α is

$$\frac{\partial X^*}{\partial \alpha} \;=\; -\frac{2\kappa(1-\beta)[2\gamma\sigma(2-\beta+\rho) + 9\kappa\gamma - 2\kappa(1+\rho)^2]}{[9\kappa\gamma + 2\gamma\sigma^2 - 2\kappa(2-\rho)(1+\rho)]^2}.$$

The denominator of the RHS is positive. Furthermore, if $2\gamma\sigma(2-\beta+\rho) > 0$, then the sign of this equation depends on the sign of $9\kappa\gamma - 2\kappa(1+\rho)^2$. By Assumption 3, $9\kappa\gamma - 2\kappa(1+\rho)^2 > 0$. Therefore,

$$\frac{\partial X^*}{\partial \alpha} \;<\; 0.$$

□

Proof. Partial derivative of X^* with respect to β is

$$\frac{\partial X^*}{\partial \beta} = \frac{2(a-\bar{c})\kappa\left[-9(1-\alpha)\kappa\gamma + 2\alpha\sigma(2+\rho)\gamma + 2(1-\alpha)(1+\rho)^2\kappa\right]}{[9\kappa\gamma + 2\gamma\sigma^2 - 2\kappa(2-\rho)(1+\rho)]^2}. \tag{19}$$

Given that the denominator of the RHS is positive, the sign of Equation (19) equals that of

$$\left[-9(1-\alpha)\kappa\gamma + 2\alpha\sigma(2+\rho)\gamma + 2(1-\alpha)(1+\rho)^2\kappa\right].$$

Assume that $-9(1-\alpha)\kappa\gamma + 2\alpha\sigma(2+\rho)\gamma + 2(1-\alpha)(1+\rho)^2\kappa > 0$. Since $\sigma = \alpha(1-\beta)$, we can transform this inequality to $-9(1-\alpha)\kappa\gamma + 2\alpha^2(1-\beta)(2+\rho)\gamma + 2(1-\alpha)(1+\rho) > 0$. We can solve this inequality for κ, obtaining

$$\kappa < \frac{2(1+\rho)}{9\gamma} + \frac{4\alpha^2(1-\beta)}{9(1-\alpha)} + \frac{2}{9}\sigma^2.$$

According to part 3 of Assumption 3, we have

$$\frac{2}{9}\sigma^2 < \kappa < \frac{2(1+\rho)}{9\gamma} + \frac{4\alpha^2(1-\beta)}{9(1-\alpha)} + \frac{2}{9}\sigma^2.$$

Therefore, if $\kappa < \frac{2(1+\rho)}{9\gamma} + \frac{4\alpha^2(1-\beta)}{9(1-\alpha)} + \frac{2}{9}\sigma^2$, then $-9(1-\alpha)\kappa\gamma + 2\alpha\sigma(2+\rho)\gamma + 2(1-\alpha)(1+\rho)^2\kappa > 0$. Similarly, if $\frac{2(1+\rho)}{9\gamma} + \frac{4\alpha^2(1-\beta)}{9(1-\alpha)} + \frac{2}{9}\sigma^2 < \kappa$, then $-9(1-\alpha)\kappa\gamma + 2\alpha\sigma(2+\rho)\gamma + 2(1-\alpha)(1+\rho)^2\kappa > 0$. Hence, we obtain two cases.

Case 1. $\kappa < \frac{2(1+\rho)}{9\gamma} + \frac{4\alpha^2(1-\beta)}{9(1-\alpha)} + \frac{2}{9}\sigma^2$. Then

$$\frac{\partial X^*}{\partial \beta} > 0.$$

Case 2. $\kappa > \frac{2(1+\rho)}{9\gamma} + \frac{4\alpha^2(1-\beta)}{9(1-\alpha)} + \frac{2}{9}\sigma^2$. Then

$$\frac{\partial X^*}{\partial \beta} < 0.$$

$\square$

C Proof of equation (13) through (16)

Proof. Partial derivative of Z^* with respect to γ is

$$\frac{\partial Z^*}{\partial \gamma} = -\frac{4(a-\bar{c})\kappa\,(2-\rho)(1+\rho)\sigma}{\{\kappa\,[9\gamma-2\rho(1-\rho)-4]+2\gamma\alpha^2(1-\beta)^2\}^2}.$$

Therefore,

$$\frac{\partial Z^*}{\partial \gamma} < 0.$$

$\square$

Proof. Partial derivative of Z^* with respect to κ is

$$\frac{\partial Z^*}{\partial \kappa} = -\frac{2(a-\bar{c})\gamma\,\sigma(9\gamma-2\rho(1-\rho)-4)}{\{\kappa\,[9\gamma-2\rho(1-\rho)+2\gamma\sigma^2]\}^2}.$$

The sign of this equation is opposite that of $(9\gamma-2\rho(1-\rho)-4)$. Under Assumption 3, this equation is negative. Therefore,

$$\frac{\partial Z^*}{\partial \kappa} < 0.$$

$\square$

Proof. Partial derivative of X^* with respect to γ is

$$\frac{\partial X^*}{\partial \gamma} = -\frac{2(a-\bar{c})\kappa(1+\rho)(9\kappa+2\sigma^2)}{[9\kappa\gamma+2\gamma\sigma^2-2\kappa(2-\rho)(1+\rho)]^2}.$$

Therefore,

$$\frac{\partial X^*}{\partial \gamma} < 0.$$

$\square$

Proof. Partial derivative of X^* with respect to κ is

$$\frac{\partial X^*}{\partial \kappa} = \frac{4(a-\bar{c})\gamma(1+\rho)\sigma^2}{[9\kappa\gamma+2\gamma\sigma^2-2\kappa(2-\rho)(1+\rho)]^2}.$$

Therefore,

$$\frac{\partial X^*}{\partial \kappa} > 0.$$

$\square$

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