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Abstract
A buyer's technical knowledge may increase the efficiency of its supplier. Suppliers, however, frequently maintain relationships with additional buyers. Knowledge disclosure then bears the risk of benefiting one's own competitor due to opportunistic knowledge transmission through the common supplier. We show that in one-shot relationships no knowledge disclosure takes place because the supplier has an incentive for knowledge transmission and, in anticipation of this outcome, buyers refuse to disclose any of their knowledge. In repeated relationships knowledge disclosure is stabilized by larger technological proximity between buyers and suppliers and destabilized by the absolute value of the knowledge.

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1 Introduction

Knowledge sharing among vertically related firms is commonly regarded as a key ingredient to efficient buyer-supplier relationships. In particular, the disclosure of technical knowledge[1] by a customer may increase the supplier's production efficiency. Kotabe et al. (2003) document this positive effect empirically for suppliers in the U.S. and Japanese automotive industry. Moreover, increasing supplier performance usually translates into lower input prices or enhanced input quality respectively.[2] Thus, buyers indeed have an incentive to disclose their technical knowledge to their suppliers.[3]

Frequently, however, firms purchase inputs from the *same* suppliers as their rivals. If a common supplier is either not able or not willing to treat obtained knowledge confidentially, the leakage of knowledge to rivals may dampen or even outweigh the gains from an increased supplier performance. According to empirical evidence such concerns are ubiquitous. Grindley, Mowery and Silverman (1994) report that manufacturers of semiconductor materials and equipment (SME) were concerned over sharing information with members of SEMATECH (the Semiconductor Manufacturing Technology Consortium) because they feared the disclosure of proprietary information to their competitors. Cassiman and Veugelers (2002) and Bönte and Keilbach (2005) find that firms which cannot protect their proprietary innovations by strategic protection mechanisms, such as complex or idiosyncratic production processes, have a lower propensity to engage in knowledge sharing R&D cooperations with their suppliers.[4]

[1] Alternative types of valuable knowledge in vertical relationships are demand and cost information, see Lee and Whang (2000) for a survey of supply chain information sharing.

[2] For instance, Dyer and Hatch (2004 a, b) relate Toyota's superior quality- and profit performance to its more intense knowledge sharing with suppliers as compared to General Motors, Ford and Daimler-Chrysler.

[3] Of course, a supplier may also have an incentive to disclose its knowledge to customers. Harhoff (1996), for instance, shows that a monopolist supplier may voluntarily disclose knowledge to customers in order to induce process and product innovations by customers, which in turn may enhance the demand for the supplier's intermediate good.

[4] Firms may also engage in horizontal knowledge sharing with firms from the same industry. Empirical evidence suggests that such direct transfer occurs (Appleyard 1996, Sattler et al. 2003, Schrader, 1991). Jost (2005) investigates theoretically the limits of

Of course, suppliers will try to meet such objections. Consider, for example, the electronic manufacturer Flextronics who builds products for a bunch of high-tech firms, including direct competitors such as Motorola and Ericsson. According to Flextronics' management the company "had been able to erect 'fire walls' to prevent proprietary information from leaking between competitors".[5] The credibility of such promises, however, is questionable if the supplier benefits from knowledge transmission. Then the disclosed knowledge may be opportunistically misappropriated by the supplier, which immediately raises the question of how much knowledge the buyer should disclose in the first place.

We seek answers to these questions by employing a four stage model. In the first stage two downstream firms, i.e. buyers, decide how much of their proprietary technical knowledge they disclose to an upstream monopolist, i.e. their common supplier. Any disclosed knowledge increases the supplier's production efficiency. In the second stage the common supplier decides how much of one buyer's knowledge it further transfers to the other one. In the third stage the supplier sets its price, i.e. the buyers' input price. In the fourth stage the downstream firms compete in output-quantities. This scenario is analyzed both for a one-shot buyer-supplier-relationship and for repeated relationships.

The combination of potential supplier opportunism and downstream competition is the key ingredient to our knowledge sharing model. Only few previous studies consider these issues. Baiman and Rajan (2002) address the role of opportunism in buyer-supplier relationships. In contrast to our work they focus on a bilateral buyer-supplier relationship in which the supplier misappropriates the information by using it for himself; for instance, the supplier may emerge as a competitor to the knowledge sharing buyer. Their setting thus reflects an arguably stronger and more costly kind of misappropriation than our knowledge-transfer scenario.

Similar to our setting Li (2002) and Zhang (2002) consider information sharing of competing downstream firms to a common supplier. In their model, however, information is about demand or cost uncertainty. As

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such horizontal knowledge sharing networks.

[5]The New York Times 2001, "Ignore the Label, It's Flextronics Inside".

the supplier takes advantage of these informations to seek more rents from its buyers, the latter suffer from disclosing their knowledge in any bilateral buyer-supplier relationship. The leakage effect of information from one downstream firm to another is negative if demand information is at stake but positive when it comes to cost information. In contrast, the disclosure of technical knowledge in our model induces a positive effect within the bilateral buyer-supplier relationship (i.e. increased production efficiency and a lower input price) whereas the leakage of technical knowledge always hurts (benefits) the revealing (receiving) downstream firm.

Harhoff et al. (2003) propose that two downstream firms may reveal their innovations because their common supplier may refine them. Yet refinements are only profitable in the case that both downstream firms adopt the improved innovation. This in turn causes a downstream firm to reveal its innovation if and only if it expects the other downstream firm to adopt it too. Our study is in contrast motivated by the abovementioned empirical studies that suggest firms to disclose their innovation specifically if these cannot be adopted too easily by their competitor or if the innovation is treated confidentially by the supplier respectively.

Our study extends the scope of previous works as we analyze explicitly the supplier's incentive to behave opportunistically. Moreover, to behave opportunistically either in a one-shot buyer-supplier relationship or in repeated relationships. Our results suggest that this distinction is crucial to understand knowledge disclosure in buyer-supplier relationships. In particular we find that buyers disclose their technical knowledge completely as long as the common supplier does not transfer 'too much' of that knowledge to their rivals. The supplier, however, has an incentive to give away all of its knowledge to downstream firms. The announcement to treat the obtained knowledge confidentially (e.g. to install 'firewalls') is thus not credible[6] (not a subgame perfect equilibrium) and, anticipating that, a downstream firm will not disclose any of its knowledge in the first place.[7]

[6]Miliou (2004) investigates the welfare effects of firewalls in a setting with exogenous spillovers from a buyer to a vertically integrated supplier. However, he leaves open the question of whether the supplier has an incentive to install a firewall.

[7]Thereby our results also indicate that the case of full knowledge sharing as analyzed

These predictions change if the buyer can threaten not to disclose its knowledge in subsequent periods. We identify two types of knowledge sharing equilibria in the repeated game. In the first one each buyer discloses its knowledge completely whereby the supplier does not further transfer 'too much' of it. In the second, more subtle one, each buyer, again, discloses its knowledge completely but the supplier further transfers all of it. This equilibrium occurs because revealing *and* receiving knowledge implies a net benefit for the downstream firms. Here, in fact, one buyer threatens the other one by not disclosing its knowledge in future periods if it did not receive an adequate amount of knowledge in return. Both types of equilibria are stabilized by a larger technological proximity between the buyers and the supplier and destabilized by the absolute value of knowledge.

The paper is arranged as follows. In section 2 we set up the model. In particular we derive the downstream firms' optimal output quantities in the fourth stage and the supplier's input price in the third stage of the model. In section 3 we analyze the downstream firms' incentives for knowledge disclosure in a one-shot relationships. In section 4 we investigate the case in which firms interact repeatedly. Section 5 concludes.

2 The Basic Model

We consider two vertically related industries where two firms in the downstream industry, $i = 1, 2$ transform the intermediate input produced by the upstream industry into a final output. The upstream industry is characterized by a monopolist supplier, u, as we are essentially interested in the case in which downstream competitors are related to a common supplier.

Our model consists of four stages. In the first stage each downstream firm (buyer) decides how much of its proprietary knowledge it discloses to the upstream monopolist (supplier). This knowledge transfer lowers the supplier's production costs. Once the upstream firm possesses the new knowledge, from i say, it decides in the second stage, whether it further transfers this knowledge to j. In the third stage the upstream firm sets the intermediate

by Ishii (2004) will not be an equilibrium.

input price and in the fourth stage the downstream firms compete in the final output market a la Cournot.

The upstream firm produces with marginal costs of production, $c - Y$, where c is an exogenous parameter, $c > Y$, and

$$Y = t(\alpha_i x_i + \alpha_j x_j), \quad i = 1, 2, \quad i \neq j \tag{1}$$

represents the amount of cost-reduction the upstream firm realizes due to the knowledge transfer of the downstream firms. In particular x_i (x_j) measures the size of i's (j's) proprietary knowledge. The endogenous variables $\alpha_i \in (0, 1)$, $i = 1, 2$, represent the fraction of x the downstream firms actually disclose to u. The upstream firm's benefit from any amount of the downstream industry's knowledge, however, might be technologically limited. The parameter $t \in (0, 1)$ captures the degree of technological proximity between the upstream firm and the downstream firms.

The downstream firms' marginal costs of production are $A+w-X_i$, where A is an exogenous parameter, $A > X_i$, w is the intermediate input price and

$$X_i = x_i + \alpha_j \beta_i x_j, \quad i = 1, 2, \quad i \neq j \tag{2}$$

is the amount of cost-reduction each downstream firm realizes due to the sum of its own proprietary knowledge, x_i, and the fraction of its rival's knowledge, x_j, that gets into its domain. The ith firm receives its rival's knowledge according to the fraction α_j, the rival has previously revealed to the upstream monopolist and the fraction $\beta_i \in (0, 1)$, $i = 1, 2$, that is transferred from firm j's knowledge to firm i via the common supplier. According to equation (2) the ith downstream firm will utilize all of its rival's knowledge if $\alpha_j = \beta_i = 1$. This implies that these firms have chosen to follow the same technological trajectories in the first place. This presumption is in line with a recent finding of Wiethaus (2005) who shows that competing firms indeed tend to adopt identical R&D approaches[8]. Since we are interested in firms' incentives to disclose their proprietary knowledge but not in their incentives to create that knowledge we will assume throughout the rest of the paper that both firms

[8]He also extends this finding to Kamien and Zang's (2000) model according which the authors had previously predicted that competing firms adopted different R&D approaches.

possess an innovation of given and identical size: $x = x_i = x_j$ [9].

We summarize these considerations in the firms' profit functions. The ith downstream firm's profit-function can be written as

$$\pi_i = (P(Q) - (A + w - X_i))q_i, \quad i = 1, 2 \tag{3}$$

where $P(Q) = a - bQ$ determines the price of the final product as a function of the firms' joint output quantity, $Q = q_i + q_j$. We assume that both downstream firms pay the same input price w, i.e. the monopolist supplier does not differentiate the input price. Without loss of generality we assume $b = 1$. Supposing that the final product is produced with a 1:1 technology (one unit of final product requiring exactly one unit of input) the upstream firm's profit-function is

$$\pi_u = (w - (c - Y))Q. \tag{4}$$

Using the standard backwards induction procedure we first derive the firms' decisions starting in the fourth stage. Differentiation of (3) with respect to q_i and q_j respectively and then solving both first-order-conditions simultaneously for q_i and q_j yield the firms' equilibrium output quantities,

$$q_i^* = \frac{a - A - w + 2X_i - X_j}{3} \quad i = 1, 2 \;\; i \neq j. \tag{5}$$

where X_i, and X_j respectively, are given by (2). We assume that the downstream firms take the price of the intermediate input w as given.

In the third stage the upstream firm sets the intermediate input price. Anticipating the downstream firms' behavior in the final product market the upstream firm maximizes its profits upon substitution of

$$Q^* = q_i^* + q_j^* = \frac{2(a - A - w) + X_i + X_j}{3} \quad i = 1, 2 \;\; i \neq j \tag{6}$$

for Q in (4). Solving the first-order-condition, $\partial\pi_u/\partial w|_{Q=Q^*} = 0$, for w yields the intermediate input price

$$w^* = \frac{2(a - A + c - Y) + X_i + X_j}{4}. \tag{7}$$

[9] Firms' R&D investments have been anaylized extensively by, among others, D'Aspremont and Jacquemin (1988) and Kamien et al. (1992) for the case of horizontally related firms and by Atallah (2002) and Ishii (2004) for the case of vertically related firms.

By (6) and (7) it is apparent that a decrease of marginal costs in the downstream industry due to an increase in knowledge (X_i, X_j) creates an *additional demand effect* for the intermediate input which in turn increases the monopolist's profit-maximizing price[10], $\partial w^*/\partial X_i > 0$, and its profits respectively. If the downstream firms, however, disclose their knowledge to the upstream firm this lowers also upstream production costs by $Y = t(\alpha_i x + \alpha_j x)$ and, as a consequence, w^*. We will refer to this latter mechanism as the *cost efficiency effect*.

3 Knowledge disclosure in a one-shot relationship

We will investigate four scenarios when analyzing the remaining stages of the game: In the first one the parameter β is assumed to be exogenous because the upstream firm does not deliberately transfer knowledge disclosed by one downstream firm to the other downstream firm. Therefore, in this scenario the game reduces to a three-stage game. In the second case the upstream monopolist decides opportunistically whether or not to transfer the disclosed knowledge at the second stage. In both scenarios the downstream firm is supposed to maximize solely its own profits when deciding about disclosure of knowledge at the first stage. In the third scenario we propose a cooperative solution between the downstream firm and the upstream monopolist.

Absence of supplier opportunism In this section we analyze a downstream firm's incentive to disclose its knowledge to the upstream monopolist assuming that the latter does not behave opportunistically.[11] In other words the supplier treats disclosed knowledge confidentially and does therefore not take any action to pass on the disclosed knowledge to the other downstream firm.

[10] Banerjee and Lin (2003) point out that this effect raises a rival's costs and may hence stimulate downstream firms' R&D.

[11] A customer's expectation that a common supplier will not exploit the vulnerabilities created by knowledge disclosure may be viewed as the customer's trust in the supplier. See e.g. Bönte (2005).

In order to obtain the ith firm's output quantity we substitute w^* for w in (5) which yields

$$q_i^{**} = \frac{2(a - A - c + Y) + x(2 + 7\alpha_j\beta_i - 5\alpha_i\beta_j)}{12} \quad i = 1, 2 \;\; i \neq j, \qquad (8)$$

given the monopolist's optimal price w^* and prior to i's knowledge disclosure to its supplier. The parameters β_i and β_j take the value zero if the upstream firm is able to keep the shared knowledge fully secret whereas positive values reflect the leakage of knowledge to downstream firms that is (here) not intended by the upstream firm. Making use of (8) and (7) we can write (3) as

$$\pi_i^* = (a - (q_i^{**} + q_j^{**}) - (A + w^* - X_i))q_i^{**} \quad i = 1, 2 \;\; i \neq j. \qquad (9)$$

Differentiating (9) with respect to α_i yields

$$\frac{\partial \pi_i}{\partial \alpha_i} = x(2t - 5\beta_j)\frac{2(a - A - c + Y) + x(2 + 7\alpha_j\beta_i - 5\alpha_i\beta_j)}{72}. \qquad (10)$$

Note that the fraction in (10) is strictly positive which means that the sign of $(2t - 5\beta_j)$ alone determines whether knowledge transfer to the upstream monopolist is profitable from a downstream firm's point of view. We state this more precisely in

Lemma 1 *There exists a critical level of knowledge leakage from the upstream firm, u, to the ith firm's rival j, which determines whether the ith firm discloses all or nothing of its knowledge to the upstream firm. Denoting this critical level β_j^c, we have*

$$\beta_j^c \geqslant \frac{2}{5}t \Longrightarrow \alpha_i^* = 0,$$

and

$$\beta_j^c < \frac{2}{5}t \Longrightarrow \alpha_i^* = 1, \quad i = 1, 2 \;\; i \neq j.$$

Proof. By (10), $\partial\pi/\partial\alpha_i > 0 \Longleftrightarrow 2t - 5\beta_j > 0$, for all $\alpha_i \in (0, 1)$.

The intuition for this result is rather straightforward if we look at the marginal effects of knowledge disclosure by firm i on its own profit and on the rival's profit in a more general way:

$$\frac{\partial \pi_i}{\partial \alpha_i} = \underbrace{\underset{>0}{\frac{\partial \pi_i}{\partial X_i}} \underset{=0}{\frac{\partial X_i}{\partial \alpha_i}}}_{\substack{direct\ effect \\ =0}} + \underbrace{\underset{<0}{\frac{\partial \pi_i}{\partial w}} \underset{(<0)}{\frac{\partial w^*}{\partial \alpha_i}}}_{\substack{price\ effect \\ (>0)}} + \underbrace{\underset{<0}{\frac{\partial \pi_i}{\partial q_j}} \underset{\gtrless 0}{\frac{\partial q_j^{**}}{\partial \alpha_i}}}_{\substack{strategic\ effect \\ \leqslant 0}}, \qquad (11)$$

$$\frac{\partial \pi_j}{\partial \alpha_i} = \underbrace{\underset{>0}{\frac{\partial \pi_j}{\partial X_j}} \underset{\geqslant 0}{\frac{\partial X_j}{\partial \alpha_i}}}_{\substack{direct\ effect \\ \geqslant 0}} + \underbrace{\underset{<0}{\frac{\partial \pi_j}{\partial w}} \underset{(<0)}{\frac{\partial w^*}{\partial \alpha_i}}}_{\substack{price\ effect \\ (>0)}} \qquad (12)$$

The direct marginal effect of knowledge disclosure on ith firm's own profit in equation (11) is zero. Consequently, the decision of the ith firm about the disclosure of knowledge to the upstream monopolist is driven by a *price effect* and a *strategic effect.* The sign of the price effect in equation (11) depends on the sign of the change of the intermediate input price: $\partial w^*/\partial \alpha_i = -\frac{1}{4}x(2t - \beta_j)$. This sign will be positive if the *cost efficiency effect*, $2t$, is stronger than the *additional demand effect,* $-\beta_j$. The strategic effect is always negative because the ith firm's knowledge reduces j's production costs and increases its output quantity respectively: $\partial q_j^{**}/\partial \alpha_i = \frac{1}{12}x(2t + 7\beta_j)$. Obviously knowledge disclosure by downstream firms will not occur unless the price effect is positive.[12]

Thus, the sign of the marginal effect of knowledge disclosure on firm i's own profit is determined by the counteracting (positive) price effect and (negative) strategic effect. In contrast, the marginal impact of knowledge disclosure by firm i on the rival's profit is always positive provided $\beta_j \neq 0$. The price effect in (12) is positive because the price effect is the same for both firms and firm i will not have an incentive to disclose knowledge if this effect is negative or zero. The direct effect is positive because $\partial X_j/\partial \alpha_i = \beta_j x$.

Rather counter-intuitively, equations (11) and (12) imply that the ith firm will disclose its technical knowledge to the upstream monopolist being aware that this benefits its rival more than itself. However, according to Lemma 1 the rival must not benefit too much. For example, given the parameter t

[12]The brackets indicate that we suppose a positive price effect.

takes the value 1, firm i will only be willing to disclose its knowledge if less than 40% of this knowledge ($\beta_j < 2/5$) leak out to the competitor.

Taken together, for any additional unit of knowledge a buyer i transfers to its supplier it hinges critically on β_j whether the additional demand of firm j does not increase w^* too much and, furthermore, the loss of firm i's competitiveness in the final product market is not too strong. Thus, downstream firms will disclose their knowledge if the upstream firm is able and willing to keep the disclosed knowledge secret ($\beta = 0$) or if the level of involuntary knowledge leakage is, at least, not to high, i.e. $\beta/t < 2/5$.[13]

Presence of supplier opportunism So far, we have assumed that the upstream firm tries to treat shared knowledge confidentially. We will now endogenize β and allow for opportunistic behavior of the supplier. To derive the upstream firm's second stage profit-function we first substitute w^* for w in (6) to get

$$Q^{**} = \frac{2(a - A - c + Y) + X_i + X_j}{6} \quad i = 1, 2 \;\; i \neq j, \tag{13}$$

the final product production quantity, given w^*. Then, keeping in mind that w^* and Q^{**} are functions of $X_i = x + \alpha_j \beta_i x, \quad i = 1, 2, \quad i \neq j$, the upstream firm maximizes

$$\pi_u^* = (w^* - (c - Y))Q^{**} \tag{14}$$

with respect to β_i. The first-order-condition,

$$\frac{\partial \pi_u}{\partial \beta_i} = \frac{1}{12}\alpha_j x(2(a - A - c + Y) + X_i + X_j) \geqslant 0 \tag{15}$$

is non-negative, which brings us to

Proposition 1 *The upstream firm will always transfer all of the knowledge it obtains from a downstream firm, i, to i's rival, j, i.e.* $\beta_i^* = 1, \quad i = 1, 2.$

[13] A critical leakage level does also exist for knowledge disclosure in *horizontal* research joint ventures (RJVs) between competitors. Atallah (2003) shows that firms will not disclose their knowledge to their RJV partners (insiders) if leakage of knowledge to rivals which are not RJV partners (outsiders) exceeds a critical level. The latter is increasing (decreasing) in the number of insiders (outsiders).

Proof. Straightforward by (15).

The reason for this result is the additional demand effect. By comparison of (13) and (15) it is obvious that for any unit of knowledge the upstream firm transfers from one downstream firm to another, it increases the demand for its own intermediate input proportionally. However, if the ith firm expects that the upstream firm has an incentive to transfer all of the knowledge it receives from i to firm j, i.e. $\beta_j^* = 1$, we can conclude with the following

Proposition 2 *In the non-cooperative case the downstream firms will not disclose any of their knowledge to their (common) upstream supplier, i.e.* $\alpha_i^* = 0, \quad i = 1, 2 \;\; i \neq j$.

Proof. Straightforward by Proposition 1 and Lemma 1.

Buyer-supplier cooperation As yet, we have assumed that the downstream and the upstream firm maximize solely their own profits when deciding about disclosure and the transfer of knowledge and our results suggest that behavior causes a knowledge sharing dilemma. However, cooperation between vertically related firms may help to overcome this dilemma. If the upstream monopolist's gain from knowledge disclosure is higher than the downstream firm's loss then the monopolist and the downstream firm might agree on knowledge disclosure. The monopolist will compensate the downstream firm for its losses; any additional profits might be split.

Such a solution is feasible if and only if the effect of the downstream firm's knowledge disclosure is positive for i's and u's joint profits. We thus differentiate

$$\pi_i^* + \pi_u^* = (a - (q_i^{**} + q_j^{**}) - (A + w^* - X_i))q_i^{**} + (w^* - (A - Y))Q^{**} \quad (16)$$

with respect to α_i. Since downstream firms are symmetric we consider a supplier's cooperation with both downstream firms. Thus we calculate $\partial(\pi_i^* + \pi_u^*)/\partial\alpha_i$ and then simplify the resulting expression by setting $i = j$. This yields

$$\left.\frac{\partial(\pi_i^* + \pi_u^*)}{\partial\alpha_i}\right|_{i=j} = x(\beta + 14t)\frac{(a - A - c + x(1 + \alpha\beta + 2\alpha t))}{36}. \quad (17)$$

In contrast to (10), (17) is strictly positive, regardless of the monopolist's further knowledge transfer, β. We can thus state

Proposition 3 *In the cooperative (joint-profit-maximizing) case the downstream firms will disclose all of their knowledge to their (common) upstream supplier, i.e.* $\alpha_i^* = 1, \quad i = 1,2 \;\; i \neq j$.

Proof. By (17) $\partial(\pi_i^* + \pi_u^*)/\partial\alpha_i > 0$, for all $\alpha_i \in (0,1)$.

Reciprocal knowledge disclosure Our model is based on the assumption that there is a unidirectional flow of knowledge from downstream firms to the upstream firm whereby the former benefit from lower input prices. One might argue, however, that a downstream firm may choose to provide information to the upstream firm not only because of the price effect but also in the expectation that it will receive valuable information in return. At least for the knowledge transfer between competitors the literature suggests that "reciprocity appears to be one of the fundamental rules governing information sharing" (Schrader, 1990, p.154).[14]

Let us therefore suppose that the supplier too possesses valuable technical knowledge which, upon disclosure, may increase the production efficiency of its buyers. Buyers still decide about knowledge disclosure in the first stage whereby the common supplier decides about disclosing its knowledge in the second stage. The supplier could announce, for instance, that she will disclose her knowledge to firm i only if the latter has already disclosed its technical knowledge.

However, the disclosure of knowledge by the upstream firm leads to an increase in the demand for the intermediate input (*demand effect*) which in turn increases the upstream firm's profit. Hence the supplier's profit maximizing decision is to fully disclose her technical knowledge to each of its buyers, even if the latter do not disclose any of their knowledge. The supplier's announcement to refuse knowledge disclosure is thus not credible and will therefore not affect the buyers' decisions. In contrast to pure horizon-

[14] Kultti and Takalo (1998) show that competitors have an incentive to share information if the exchange is not too asymmetric.

tal knowledge disclosure, reciprocity will not facilitate knowledge disclosure from buyers to a common supplier.

4 Knowledge disclosure in repeated relationships

We consider now the case in which firms interact repeatedly. In particular we assume that the following (previously defined) stage game is repeated infinitely: (1) downstream firms choose α_i, (2) the upstream firm chooses β_i, (3) the upstream sets w and (4) the downstream firms determine their output quantities, q_i. We assume that with respect to the stage game's third stage and fourth stage no cooperation takes place, that is the stage game's subgame perfect equilibria as given by (7) and (8) remain unchanged.

What kind of cooperation is attainable in stages one and two of the infinitely repeated game? First, the upstream firm u can promise not to behave opportunistically by disclosing not too much of i's knowledge to j, i.e. $\beta_j \leqslant 2/5t$. That is the common supplier installs a *weak firewall.* Secondly, even if u behaves opportunistically, i.e. $\beta_i = \beta_j = 1$, the downstream firms may still disclose knowledge to the upstream firm, as the *full transmission* outcome, $\alpha_i = \alpha_j = \beta_i = \beta_j = 1$ is Pareto superior to the no disclosure subgame perfect equilibrium of the one-shot game. We will investigate these settings in more detail below.

Weak firewall setting Suppose the following trigger strategy[15] by the ith downstream firm: in the first period it fully discloses its knowledge to the upstream firm, $\alpha_i = 1$. In the t^{th} stage, if firm u has maintained a weak firewall of $\beta_j \leq 2/5t$ in all $t-1$ periods then the ith firm plays $\alpha_i = 1$; otherwise it plays the subgame-perfect outcome of the stage game, $\alpha_i = 0$.

Since downstream firms are symmetric we suppose an identical behavior. Then let $\pi_u^{2/5}$ denote u's weak firewall profit, i.e. both downstream firms

[15]We employ trigger strategies to derive some basic comparative static results regarding the stability of cooperative solutions. Abreu's (1986 and 1988) optimal punishment strategies would increase the stability of cooperative solutions relative to trigger strategies.

disclose their knowledge and $\beta_j = \beta_i = 2/5t$; let π_u^1 denote denote u's cheat profit, i.e. both downstream firms disclose their knowledge and the upstream firm behaves opportunistically ($\beta_j = \beta_i = 1$) and let π_u^{00} denote u's profit if neither downstream firm discloses its knowledge to u.[16] Computing the respective profits by (14), (13) and (7) yields

$$\pi_u^{2/5} = \frac{1}{6}(a - A - c + \left[1 + \frac{12}{5}t\right] x)^2, \tag{18}$$

$$\pi_u^1 = \frac{1}{6}(a - A - c + [2 + 2t]\, x)^2. \tag{19}$$

The squared bracketed terms in (18) and (19) reveal that the upstream firm has indeed a short-term incentive to behave opportunistically and to transfer the received knowledge completely but, as indicated by

$$\pi_u^{00} = \frac{1}{6}(a - A - c + x)^2, \tag{20}$$

the upstream firm will suffer from this opportunistic behavior in subsequent periods when the downstream firms withhold their knowledge. The supplier will maintain its weak firewall, i.e. $\beta_j = \beta_i = 2/5t$, if

$$\frac{1}{1-\delta}\pi_u^{2/5} \geqslant \pi_u^1 + \frac{\delta}{1-\delta}\pi_u^{00}, \tag{21}$$

where $\delta = (1-p)/(1+r)$ is the common discount rate, p is the probability that the game ends immediately and r is an interest rate. Solving (21) for δ yields the critical discount factor to sustain the weak firewall equilibrium, δ_w:

$$\delta_w \geqslant \frac{(5-2t)(10(a-A-c) + (15+22t)x)}{25(1+2t)(2(a-A-c) + (3+2t)x)}. \tag{22}$$

Proposition 4 *Maintenance of a weak firewall, $\beta_i = \beta_j = 2/5t$ and repeated downstream knowledge disclosure, $\alpha_i = \alpha_j = 1$, is stabilized by an increase in the technological proximity between the downstream and the upstream firm, $\partial\delta_w/\partial t < 0$, and destabilized by an increase in the value/amount of knowledge, $\partial\delta_w/\partial x > 0$.*

[16] Recall that for the supplier there is no need to promise a knowledge transmission less than $2/5t$ because buyers themselves benefit from disclosing their knowledge as long as $\beta_i < 2/5t$, $i = 1, 2$. If buyers are indifferent about disclosing their knowledge to the supplier (i.e. $\beta_i = 2/5t$) we assume they will disclose.

Proof. The derivatives are contained in the appendix.

The more the upstream firm is able to utilize the received knowledge directly (via t), the more, of course, it will miss this knowledge in the future once downstream firms withhold it. Therefore closer technological proximity stabilizes a supplier's non-opportunistic maintenance of a firewall. On the other hand the upstream firm's incentive to further transfer the received knowledge is driven by the additional demand effect which is of course stronger the larger the amount/value of knowledge, x, that is transferred. Accordingly a larger amount/value of knowledge destabilizes non-opportunistic behavior by the upstream firm.

Full transmission setting Suppose now the upstream firm behaves opportunistically, $\beta_i = \beta_j = 1$. However, a downstream firm may still disclose its knowledge provided that it receives knowledge from its rival in return. The downstream firms anticipate that the upstream firm acts as a knowledge transmitter and may engage in (implicit) knowledge sharing with their rival. In particular, the ith firm may employ the following trigger strategy: in the first period it fully discloses its knowledge to the upstream firm, $\alpha_i = 1$. In the t^{th} stage, if both firms, $i = 1, 2$, have fully disclosed their respective knowledge in all $t-1$ periods then the ith firm plays $\alpha_i = 1$; otherwise it plays the subgame-perfect outcome of the stage game, $\alpha_i = 0$.

Let π_i^{11} denote the ith firm's profit if both firms disclose their knowledge, π_i^{01} if only $j \neq i$ and π_i^{00} if neither firm discloses its knowledge. Then by (9), (8) and (7) we have

$$\pi_i^{11} = (\frac{1}{6}(a - A - c) + \left[\frac{1}{3} + \frac{1}{3}t\right] x)^2, \tag{23}$$

$$\pi_i^{01} = (\frac{1}{6}(a - A - c) + \left[\frac{3}{4} + \frac{1}{6}t\right] x)^2. \tag{24}$$

By the squared bracketed terms in (23) and (24) it is apparent that for any $x > 0$, π_i^{01} strictly exceeds π_i^{11}. This is due to the competitive advantage the ith firm can achieve relative to its counterpart in the product-market if j discloses but i withholds its knowledge. The squared bracketed term also reveals that the incentive to deviate from the knowledge sharing strategy decreases the more the upstream firm can utilize downstream firms' knowledge, as captured by a larger t. Finally note that the downstream firms' profits of the one-shot non-disclosure equilibrium,

$$\pi_i^{00} = (\frac{1}{6}(a - A + x))^2 \tag{25}$$

are clearly smaller than those given by (23) and (24). The ith firm continues to disclose its knowledge as long as

$$\frac{1}{1-\delta}\pi_i^{11} \geqslant \pi_i^{01} + \frac{\delta}{1-\delta}\pi_i^{00} \tag{26}$$

where the discount rate δ is defined as above. Solving (26) for δ yields the critical discount factor to sustain the knowledge sharing equilibrium, δ_f:

$$\delta_f \geqslant \frac{(5-2t)(4(a-A-c)+(13+6t)x)}{(7+2t)(4(a-A-c)+(11+2t)x).} \tag{27}$$

Proposition 5 *Full knowledge transmission, $\beta_i = \beta_j = 1$, and repeated downstream knowledge disclosure, $\alpha_i = \alpha_j = 1$, is stabilized by an increase in the technological proximity between the downstream and the upstream firm, $\partial\delta_f/\partial t < 0$, and destabilized by an increase in the value/amount of knowledge, $\partial\delta_f/\partial x > 0$.*

Proof. The derivatives are contained in the appendix.

The intuition behind this result is that downstream firms not only benefit directly from each other's knowledge but also due the reduction of the intermediate input price. Of course the latter benefit occurs only to the extent to that the downstream firms' knowledge lowers also the upstream firm's production costs, as captured by t. Hence technological proximity between vertically related firms stabilizes knowledge disclosure via the cost efficiency effect (see (7)). In contrast a larger value of the information to be shared, x, increases the downstream firms' incentives to achieve a short-term competitive advantage more than it increases the benefit of the cost-efficiency effect. Thus more valuable information destabilize knowledge disclosure.

Comparison of the weak firewall and the full transmission equilibrium Which of the two equilibria is more likely to come about given that their stability is ensured by (22) and (27)? We would expect the Pareto-superior setting to be chosen by the firms. By Proposition 1 the upstream firm will certainly prefer the full-disclosure setting 2. It remains to be validated which setting appears beneficial from the downstream firms' point of view. We thus need to compare the downstream firms' disclosure profits of the full transmission setting, π_i^{11} as given by (23), with the downstream firms' profits in the weak firewall setting. Let $\pi_i^{2/5}$ denote the latter profit, i.e. $\alpha_i = \alpha_j = 1$ and $\beta_j = \beta_i = 2/5t$. Then by (9), (8) and (7) we get

$$\pi_i^{2/5} = (\frac{1}{6}(a - A - c) + \left[\frac{1}{6} + \frac{2}{5}t\right] x)^2,$$

which is smaller than the profits given by (23). Thus, downstream firms tend to fully disclose their knowledge even under 'opportunistic' behavior of the supplier. Obviously, in the full disclosure setting the behavior of the supplier is not really opportunistic. In fact, each downstream firm anticipates that it is 'cheated' in the same way by the common supplier as its rival. The upstream firm acts as an intermediary that guarantees the complete transfer of knowledge disclosed by downstream firms. Though downstream firms could just as well engage in a direct (horizontal) exchange of knowledge, the indirect exchange via the common supplier generates an extra benefit: it lowers the input price if $t > 0$. This effect stabilizes the knowledge sharing equilibrium and does not exist in pure horizontal knowledge sharing.

5 Summary and Conclusion

We have analyzed the conditions for knowledge disclosure in buyer-supplier relationships. The key feature of our model is the notion of a *common* supplier through which knowledge disclosed by one buyer may leak out to the other one. Downstream knowledge disclosure thus bears the risk of benefitting one's rival. In such a setting the conditions for knowledge disclosure by buyers (see Table 1, second column) are driven by the anticipated behavior of the common supplier (third column) and the mode in which knowledge disclosure takes place (first column).

The analysis of the one-shot relationship setting provides the following results:

Knowledge disclosure mode	Buyers' knowledge disclosure, α^*	Supplier's knowledge transmission, β^*
One-shot relationship		
absence of supplier opportunism*	$100\% \Leftrightarrow \beta < 40\%$ $0\% \Leftrightarrow \beta > 40\%$	exogenous
presence of supplier opportunism	0%	100%
buyer-supplier cooperation	100%	100%
reciprocal exchange	0%	0%
Repeated relationships		
weak firewall*	100%	40%
full transmission	100%	100%

* The displayed results imply t=1, for details see Lemma 1 and section 4.

Table 1: Equilibrium solutions of the game's first stage (buyers' knowledge disclosure) and second stage (supplier's knowledge transmission) respectively

If the downstream firm is confident that the common upstream supplier cannot transmit 'too much' of the disclosed knowledge to its competitor, full knowledge disclosure occurs even if the competitor benefits more from this more than the disclosing firm itself. In contrast, downstream knowledge disclosure will not occur at all if buyers anticipate opportunistic behavior of their common supplier. In fact the supplier's announcement to treat the obtained knowledge confidentially (to install a firewall) is not credible in a one-shot relationship.

One way to overcome this knowledge sharing dilemma is buyer-supplier cooperation (i.e. joint profit maximization). The upstream firm can compensate the downstream firm for its losses, as the supplier's gain from knowledge disclosure is higher than the buyer's loss. On the other hand, reciprocal knowledge exchange does not facilitate knowledge disclosure by downstream firms. The upstream firm's announcement to hold back its own knowledge as a response of refused downstream knowledge disclosure is not credible.

In the case of repeated relationships we identify two possible equilibria:

In the first one buyers proceed with complete knowledge disclosure as long as the supplier maintains a weak firewall. In the second, more subtle one, knowledge disclosure occurs even under full knowledge transmission through the supplier. Here the supplier acts as an intermediary for implicit downstream knowledge sharing. Both the weak firewall and the full transmission setting are stabilized by an increase in the degree of technological proximity between the downstream and the upstream firm whereas they are destabilized by an increase in the value/amount of knowledge. The latter suggests that a firm's disclosure of *incremental* innovations is more likely than disclosure of *major* innovations.

As a by-product we provide an additional explanation for *intra*industry knowledge spillovers. These are usually regarded as an *in*voluntary leakage of knowledge. According to our results intraindustry spillovers may well be the result of voluntary knowledge disclosure to suppliers and further knowledge transmission respectively. A higher degree of technological proximity between customers and suppliers facilitates voluntary *inter*industry knowledge spillovers as well as intraindustry spillovers.

Our model has several possible extensions. One can analyze, for instance, how product differentiation affects downstream firms' incentives for knowledge disclosure. In our model firms in the downstream industry make use of one input to produce a homogenous final product. This implies that all firms in the downstream industry benefit from lower input prices due to knowledge disclosure in the same way. Suppose that firms in the downstream industry offer differentiated products and that specific intermediate inputs are required to produce them. Then, it is not guaranteed that knowledge disclosure by one downstream firm leads to identical price reductions for all intermediate inputs. Moreover, varying degrees of competition in the upstream and the downstream industry may also influence the results. Furthermore, our model with symmetric downstream firms can be extended to one with asymmetric firms which differ, for instance, with respect to their ability to make use of the rival's knowledge.

Appendix

Proposition 4 By (22) we calculate

$$\frac{\partial \delta_w}{\partial t} = -\frac{24(10((a-A)^2+c^2)+f_1+f_2+f_3)}{(25(1+2t)^2(2(a-A-c)+(3+2t)x))^2} < 0,$$

where

$$\begin{aligned} f_1 &= (a-A)(25+24t+4t^2)x \geqslant 0, \\ f_2 &= (15+36t+28t^2)x^2 \geqslant 0, \\ f_3 &= (20(a-A)+(25+24t+4t^2)x)c > 0, \end{aligned}$$

and

$$\frac{\partial \delta_w}{\partial x} = \frac{24t(5-2t)(a-A-c)}{(25(1+2t)(2(a-A-c)+(3+2t)x))^2} > 0.$$

Proposition 5 By (27) we have

$$\frac{\partial \delta_f}{\partial t} = -\frac{16(24((a-A)^2+c^2)+g_1+g_2+g_3)}{(7+2t)(4(a-A-c)+(11+2t)x)^2} < 0,$$

with

$$\begin{aligned} g_1 &= (a-A)(109+52t+4t^2)x \geqslant 0, \\ g_2 &= (127+148t+28t^2)x^2 \geqslant 0, \\ g_3 &= (48(a-A)+(109+52t+4t^2)x)c > 0. \end{aligned}$$

Finally note that

$$\frac{\partial \delta_f}{\partial x} = \frac{8(5+8t-4t^2)(a-A-c)}{(7+2t)(4(a-A-c)+(11+2t)x)^2} > 0.$$

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