Vertical learning alliances and partial equity ownership in the presence of performance spillovers

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Abstract

Under vertical alliances, buyers often educate their partner suppliers on the principles of advanced production systems such as "lean production" and "just-in-time system". Once a supplier acquires knowledge from its partner buyer, the supplier can often apply the acquired knowledge, at least to a certain extent, to serve other buyers outside of the vertical alliance ("performance spillovers"). Performance spillovers can reduce a buyer's incentives to educate its partner supplier because, if a buyer's investment in educating its partner supplier increases the supplier's productivity to serve other buyers, the buyer's investment ends up increasing the supplier's outside option. This leads to the buyer's under-investment in its efforts to educate the supplier.

The objective of this paper is to study the role of partial equity ownership (PEO) arrangement in mitigating the buyer's under-investment in vertical learning alliances. We show that the buyer's PEO in its partner supplier mitigates the under-investment problem because it internalizes a part of the price that the buyer pays to the supplier. At the same time, PEO decreases the supplier's investment to improve its own productivity. This trade-off determines the equilibrium level of PEO in our model. Regarding welfare consequences of PEO, we find, in contrast to the standard notion that PEO is anticompetitive and hence welfare reducing, that PEO can increase welfare. This finding leads us to a new policy implication of PEO. That is, a welfare maximizing social planner who can announce a maximum permissible level of PEO may entirely permit, partially permit, or prohibit PEO, depending on the degree of performance spillovers relative to the importance of the supplier's investment. We also consider an extension of our model in which the spillover rate is endogenously determined through the link between performance spillovers and asset specificity.

JEL classification: L10, L20, L40

Keywords: Performance spillovers, under-investment, partial equity ownership, vertical alliances, welfare, policy

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1 Introduction

It has been widely recognized in the management literature that one of the most fundamental objectives of strategic alliances is the transfer of knowledge between partner firms.[1] Under vertical alliances, buyers often educate their partner suppliers on the principles of advanced production systems such as "lean production" and "just-in-time system" (Dyer and Hatch, 2006; Dyer and Nobeoka, 2000; Kotabe, Martin, and Domoto, 2003).[2] For example, Mesquita, Anand, and Brush (2008) point out that Toyota and John Deere, leaders in the automotive and equipment industries respectively, have made substantial investments in their supplier development programs, believing they can establish a supply-base advantage.

Once a supplier acquires knowledge from its partner buyer, the supplier can often apply the acquired knowledge, at least to a certain extent, to serve other buyers outside of the vertical alliance (Dyer and Hatch, 2006; Mesquita, Anand, and Brush, 2008). In what follows, a supplier's redeployment of knowledge acquired from its partner buyer to other buyers is referred to as performance spillovers, following Mesquita, Anand, and Brush (2008). Performance spillovers can reduce a buyer's incentives to educate its partner supplier because, if a buyer's investment in educating its partner supplier increases the supplier's productivity to serve other buyers, the buyer's investment ends up increasing the supplier's outside option. This leads to the buyer's under-investment in its efforts to educate the supplier.

How can the buyer's under-investment problem be resolved? Contracting can help resolve or mitigate the problem if knowledge to be transferred within vertical alliances is verifiable. However, knowledge is often tacit and non-verifiable, and contracting can play, at best, the limited role in the transfer of tacit knowledge. Several studies have found that equity ownership plays a critical role in facilitating the transfer of tacit knowledge. Using patent citations as a proxy for knowledge flows, Mowery, Oxley and Silverman (1996) and Gomes-Casseres, Hagedoorn and Jaffe (2006) empirically explored the effects of equity ownership between alliance partners on the extent of knowledge flow. Empirical results of both studies supported the hypothesis that equity ownership enhances the extent of knowledge flow between alliance partners.

The objective of this paper is to study the role of partial equity ownership (PEO) arrangement in mitigating the buyer's under-investment in vertical learning alliances, and explore its policy implications. We consider a simple vertical structure consisting of one upstream supplier (denoted by U) and two downstream manufacturers (denoted by D_1 and D_2). Imagine, as an example, that U is a producer of manufacturing machines for downstream firms, where U cannot serve more than one downstream firm due to capacity constraint. Each D_i ($i = 1, 2$)

[1]See Hamel, 1991; Mowery, Oxley and Silverman, 1996; Gomes-Cassers, Hagedoorn and Jaffe, 2006; Oxley and Wada, 2009.

[2]The logic here is that buyers accumulate a body of cutting-edge knowledge, taking advantage of their network center hub positions, and then teach less knowledgeable suppliers in order to garner supply chain competitiveness (Mesquita, Anand, and Brush, 2008).

requires one set of machines to produce their downstream goods. The goods produced by these downstream firms do not compete with one another for consumer demand.

U and D_1 are partners of a vertical learning alliance. D_1 chooses the level of knowledge that it transfers to U. Larger amount of knowledge transfer increases the productivity of U's machine for D_1's production, but D_1 must incur higher costs for knowledge transfer. And it also increases the productivity of U's machine for D_2's production, where the rate of performance spillovers is denoted by $\beta \in [0, 1]$. As β increases, D_1's knowledge transfer becomes more useful for U to serve D_2, and it becomes equally useful when β reaches 1. We find that the level of D_1's knowledge transfer is less than the level that maximizes the joint profit of D_1 and U. Because of performance spillovers, knowledge transfer increases the price of the machine for D_1, and D_1 takes this into account when it chooses the amount of knowledge transfer. Hence D_1 transfers smaller amount of knowledge as β increases, leading to an under-investment.

We show that PEO between U and D_1 can mitigate the under-investment problem of D_1's knowledge transfer. Suppose that U and D_1 jointly choose the level of D_1's partial ownership of U's equity, denoted by ϕ, through Nash bargaining. Once ϕ is chosen, D_1 chooses the level of knowledge transfer to maximize its profit. U also chooses the level of its own investment in increasing the productivity of the machine for downstream firms. PEO mitigates D_1's under-investment because it internalizes the price of the machine. That is, when D_1 owns ϕ fraction of U's equity, ϕ fraction of the machine's price belongs to D_1, and hence D_1's incentive for knowledge transfer increases as ϕ increases. At the same time, ϕ decreases U's incentive for investment, because ϕ fraction of the benefit from U's investment is captured by D_1. This trade-off is balanced out at the equilibrium level of PEO, denoted by ϕ^*.

What are the welfare consequences of PEO in our model? We find, in contrast to the standard notion that PEO is anticompetitive and hence welfare reducing, that PEO can increase welfare. We consider a variant of our model in which the social planner, rather than U and D_1, choose the level of PEO to maximize total surplus. Let ϕ^w denote the welfare maximizing level of PEO, and consider the social planner's choice of ϕ using $\phi = \phi^*$ as a benchmark. When U and D_1 choose $\phi = \phi^*$ in equilibrium, they ignore the effect of D_1's productivity improvement on consumer surplus. This implies that D_1's productivity under $\phi = \phi^*$ is lower than the socially optimal level. How can the social planner further increase D_1's productivity? Suppose that the social planner increases ϕ from $\phi = \phi^*$. This reduces U's incentive for investment, but increases D_1's incentive for knowledge transfer. We find that the latter positive effect on D_1's productivity overshadows the former negative effect, implying $\phi^w > \phi^*$, when U's investment is less important and β is relatively large.

This finding leads us to a new policy implication of PEO. Consider a welfare maximizing social planner who can announce a maximum permissible level of PEO, denoted by $\tilde{\phi}$, before U and D_1 choose the level of PEO. We then find that the social planner announces $\tilde{\phi} = \phi^w$ if $\phi^w < \phi^*$ but no need to announce any $\tilde{\phi}$ if $\phi^w \geq \phi^*$. That is, the planner's optimal policy can be permit, partially permit, or prohibit (when $\phi^w = 0$) PEO, depending on the degree of performance spillovers and the importance of U's investment.

The rate of performance spillovers β is a key element of our model, where β is an exogenous parameter in our base model. We consider an extension of our model in which the rate of performance spillovers is endogenously determined through the link between performance spillovers and asset specificity and discuss robustness of our main results. The extension exhibits robustness of the welfare consequences of our base model. That is, we identify a pattern in the extension that, as the importance of U's investment decreases, the endogenously determined degree of performance spillovers increases. And, $\phi^w > \phi^*$ holds when the importance of U's investment is smaller than a threshold.

The remainder of the paper is organized as follows. Section 2 discusses our paper's relationship to the literature. Section 3 presents our model that incorporates performance spillovers into a double-sided moral hazard setup. Section 4 characterizes the equilibrium and shows that the equilibrium level of PEO can be strictly positive. Section 5 explores welfare consequences and policy implications of our analyses. Section 6 analyzes an extension of our model in which the degree of performance spillovers is endogenously determined, and discusses robustness of our main results. Section 7 concludes the paper.

2 Relationship to the literature

Outsourcing is often accompanied by the risk of information leakage. That is, if a downstream producer procures an intermediate product from an upstream supplier, the producer's trade secrets may be shared with the supplier, who may the leak the information to other downstream firms. These concerns are typical in R&D intensive industries (Milliou, 2004). Baccara (2007) analyzes the R&D investment of firms that decide between outsourcing and in-house production when the risk of information leakage is present in a general equilibrium model, and explores the tradeoff between hiring efficient contractors (upstream suppliers) and protecting R&D information from expropriation by choosing in-house production. Several papers theoretically study the impact of vertical integration on competition, welfare, and R&D incentives in the presence of the risk of information leakage (Hughes and Kao, 2001; Milliou, 2004; Thomas, 2011; Allain, Chambolle, and Rey, 2011; Milliou and Petrakis, 2012). A main idea explored in these papers is that a vertically integrated upstream supplier can be more tempted to pass on trade secrets learned from another downstream producer to its own downstream subsidiary. Lai, Riezman, and Wang (2009) study the role that revenue-sharing contracts can play in preventing information leakage (see below for more details).

Performance spillovers, the focus of our paper, are fundamentally different from information leakage. In our framework, a downstream producer can improve an upstream supplier's performance by transferring its knowledge with costs. Performance spillovers occur when the supplier can apply the acquired knowledge to serve other producers. In contrast, information leakage occurs when valuable information possessed by a downstream producer is unavoidably shared with an upstream supplier through the process of outsourcing, where the supplier can sell the acquired information to other downstream firms.

Despite the prevalence of performance spillovers (see, for example, Wang, Xiao, and Yang (2011) and references therein), few theoretical analyses have previously addressed performance spillovers, to the best of our knowledge. The only exception we know of is Wang, Xiao, and Yang (2011), who incorporate performance spillovers in the stochastically proportional yield model, commonly used in the operations research literature. In their model, two manufacturers share a common component supplier, which has a production process that is subject to random output. Both manufacturers can exert effort to improve the reliability of the supplier's production process, where supplier improvement due to one manufacturer's effort may be applicable for the supplier to serve the other manufacturer. Wang, Xiao, and Yang characterize the manufacturers' equilibrium improvement efforts and provide managerial insights on the market characteristics that influence their equilibrium improvement efforts.

We study the role that PEO arrangements can play in inducing a downstream manufacturer's knowledge transfer to an upstream supplier in the presence of performance spillovers, and explore welfare consequences and policy implications of PEO arrangements in this context. In Wang, Xiao, and Yang (2011), manufacturers' efforts transfer their knowledge to the supplier to improve its reliability. Contracting can then be helpful when the knowledge to be transferred is verifiable and PEO can be helpful when it is tacit and non-verifiable, but neither of them is considered in their analysis. Also, in our model the upstream firm can make an investment to increase effectiveness of its product for downstream firms, whereas in Wang, Xiao, and Yang the upstream supplier does not make such an investment.[3]

Lai, Riezman, and Wang (2009) study the role of revenue-sharing contracts, which is theoretically similar to the role of PEO arrangements in our setup, in the outsourcing of R&D activities accompanied by the risk of information leakage. In their model, downstream manufacturers compete in a monopolistically competitive industry, where each manufacturer decides whether to outsource its cost-reducing R&D or to do it in-house. Research subcontracting firms have a comparative advantage in R&D activities. However, if R&D is outsourced, the manufacturer's trade secret is obtained by the research firm, which can sell the information to other manufacturers.

Our contribution to the analysis of performance spillovers can be viewed as parallel to Lai, Riezman, and Wang's contribution to information leakage. In our model, PEO arrangement mitigates the downstream manufacturer's under-investment problem due to performance spillovers, whereas in Lai, Riezman, and Wang's model, a revenue-sharing contract may prevent a research firm's information leakage, inducing the downstream manufacturer to outsource R&D activi-

[3]They point out such an extension as a possible future research.

ties. In terms of policy implications, we consider a social planner who can impose maximum permissible level of PEO, where as Lai, Riezman, and Wang consider an intellectual property policy of tighter protection of trade secrets.

Our model setup is based on double-sided moral hazard models. Bhattacharyya and Lafontaine (1995) put forth and analyze such a model in the context of franchise relationship. In business-format franchising, the franchisor is typically responsible for providing training and general support to her franchisees, and the franchisee is responsible for managing the outlet on a day-to-day basis. In their model, efforts exerted by the franchisee and the franchisor together determine their total monetary return, where the monetary return is contractible but effort levels are not. Bhattacharyya and Lafontaine show, among other things, that the optimal sharing rule of the monetary return can be represented by a linear contract. We incorporate performance spillovers in this framework, study the role of PEO arrangements, and explore their welfare consequences and policy implications.

3 The model

We consider a vertical structure consisting of one upstream supplier (denoted by U) and two downstream manufacturers (denoted by D_1 and D_2). U produces one unit of an intermediate product with zero costs. Each D_i $(i = 1, 2)$ has zero fixed costs and a constant marginal cost of production, and requires one unit of the intermediate product to produce their downstream goods. The goods produced by these downstream firms do not compete with one another for consumer demand.

U and D_1 are partners of a vertical learning alliance. U chooses a level of investment, denoted by x (≥ 0), that increases effectiveness of its product for downstream firms. Also, D_1 chooses a level of investment, denoted by e (≥ 0), that increases effectiveness of U's product for D_1. Denote investment costs of U and D_1, respectively, by $G(x)$ and $K(e)$, where $G'(\cdot) > 0$, $G''(\cdot) > 0$, $K'(\cdot) > 0$, and $K''(\cdot) > 0$. The level of D_1's investment, e, can be interpreted as the amount of D_1's knowledge transferred to U, where $K(e)$ is the cost for knowledge transfer. Levels of investment, x and e, are observable but not contractible.

D_1's constant marginal cost is $c - \theta x - e$ if it uses U's input, whereas D_2's constant marginal cost is $c - \theta x - \beta e$ if it uses U's input, where $\theta > 0$ and $\beta \in [0, 1]$. Notice that, under our interpretation of e as the level of D_1's knowledge transferred to U, β represents the rate of performance spillovers. D_i $(i = 1, 2)$ can purchase one unit of the input from a spot market at the fixed price, which we normalize at zero. D_i's constant marginal cost under this option is c. That is, for both D_1 and D_2, the quality of the input purchased from the spot market is inferior to the input produced by U.

One interpretation of this model setup is that U produces manufacturing machines for a downstream firm, where U cannot serve more than one downstream firm due to capacity constraint. In what follows, we describe and analyze our model under this interpretation, where U produces one machine at zero (normalization) costs ("one" should be interpreted as a number of machines required by one downstream firm). Also, we assume that the machine is sold by auction through the following rule: D_1 and D_2 bid simultaneously. If the bids made by D_1 and D_2 are different, the firm with the higher bid will get the machine, and if it is a tie, each downstream firm has equal probability of getting the machine.

Because the levels of investment are not contractible and D_1's investment partially benefits D_2 due to performance spillovers, D_1 may lack the proper incentives to invest. As an improvement to this incentive problem, we introduce partial equity ownership (PEO) arrangement, whereby D_1 holds U's stocks by a share $\phi \in [0, 1]$. PEO helps D_1 to internalize part of the performance spillovers, which is likely to boost D_1's investment incentives. But, at the same time, PEO tends to decrease U's investment incentives, because U no longer owns all of the company's equities.

Given the above settings, we consider the following four-stage game.

[**Stage 1**] U and D_1 negotiate the level of PEO (ϕ) and the amount of monetary transfer (F) through Nash bargaining.

[**Stage 2**] U and D_1 simultaneously and independently choose x and e, respectively, by incurring costs.

[**Stage 3**] U sells the machine by auction.

[**Stage 4**] D_1 and D_2 choose some strategic variables and their profits realize.

4 Equilibrium characterization: PEO as an equilibrium outcome

The backward induction approach is used to solve for the subgame perfect Nash equilibrium of the four-stage game.

The forth stage

For convenience of explanation, we assume that there are three plants, plant 0, 1, and 2. Initially, plant 0 is exclusively owned by U, plant 1 is exclusively owned by D_1, and plant 2 is exclusively owned by D_2. U and D_1 can engage in a PEO arrangement, under which D_1 pays F to purchase ϕ of plant 0's shares from U.[4]

Plant i's profit exclusive of the investment cost (if any) and the purchasing cost of the machine (if any) is denoted by $\pi(c_i)$, where c_i is the constant marginal cost and $i = 1, 2$.

[4]We assume that PEO arrangement is just a silent financial interest and it gives D_1 no control power over U. That means that, regardless of whether there is PEO arrangement or not, the investment decisions in the second stage of the game will always be made unilaterally.

Furthermore, the profit function is assumed to be continuously differentiable with the following properties, $\pi'(\cdot) < 0$ and $\pi''(\cdot) > 0$. As the production cost of the machine is normalized to be 0, if the machine is sold at price t, the profit of plant 0 would be t.

Given the above settings, if D_1 buys the machine at price t, the profits of the three firms would be

$$\begin{aligned} \Pi_U &= (1-\phi)t - G(x) + F \\ \Pi_{D_1} &= \pi(c-\theta x - e) - (1-\phi)t - K(e) - F \\ \Pi_{D_2} &= \pi(c) \end{aligned} \quad ,$$

and if D_2 buys the machine at price t, the profits of the three firms would be

$$\begin{aligned} \tilde{\Pi}_U &= (1-\phi)t - G(x) + F \\ \tilde{\Pi}_{D_1} &= \pi(c) + \phi t - K(e) - F \\ \tilde{\Pi}_{D_2} &= \pi(c-\theta x - \beta e) - t \end{aligned} \quad .$$

The third stage

In the third stage of the game, the machine is sold by auction. Lemma 1 identifies the winner of the bid and the price of the machine.

Lemma 1. *If $\beta < 1$, D_1 will win the bid and the price of the machine is $\pi(c-\theta x-\beta e) - \pi(c)$.*

Proof. Supposing that the bids of D_1 and D_2 are b_1 and b_2, respectively; then, if $b_1 > b_2$, D_1 gets the machine and its profit will be $W = \pi(c-\theta x - e) - (1-\phi)b_1 - K(e) - F$, if $b_1 = b_2 = b$, D_1 gets the machine with probability 50% and its profit will be $T = (1/2)[\pi(c-\theta x - e) + \pi(c)] - (1/2)(1-2\phi)b - K(e) - F$, and if $b_1 < b_2$, D_2 gets the machine and D_1's profit will be $L = \pi(c) + \phi b_2 - K(e) - F$. Given this, D_1's best strategy should be

$$b_1(b_2) = \begin{cases} b_2 + \epsilon & \text{if} \quad b_2 < \pi(c-\theta x - e) - \pi(c) \\ b_2 & \text{if} \quad b_2 = \pi(c-\theta x - e) - \pi(c) \\ b_2 - \epsilon & \text{if} \quad b_2 > \pi(c-\theta x - e) - \pi(c) \end{cases} \quad ,$$

where ϵ is an infinitely small positive number. Similarly, it can be proved that D_2's best strategy should be

$$b_2(b_1) = \begin{cases} b_1 + \epsilon & \text{if} \quad b_1 < \pi(c-\theta x - \beta e) - \pi(c) \\ b_1 & \text{if} \quad b_1 = \pi(c-\theta x - \beta e) - \pi(c) \\ b_1 - \epsilon & \text{if} \quad b_1 > \pi(c-\theta x - \beta e) - \pi(c) \end{cases} \quad .$$

As $\pi(c-\theta x-e) > \pi(c-\theta x-\beta e)$ for $\beta < 1$, D_1 will win the bid and the price of the machine is $\pi(c-\theta x - \beta e) - \pi(c) + \epsilon$. Without any loss, in what follows, ϵ is omitted from the expression of the machine price. □

The second stage

From Lemma 1 we know that, if performance spillovers are not perfect, D_1 will win the bid at the expense of $t = \pi(c - \theta x - \beta e) - \pi(c)$. Given this, the profit functions of U and D_1 can be expressed as

$$\Pi_U = (1-\phi)[\pi(c-\theta x-\beta e) - \pi(c)] - G(x) + F, \tag{1}$$

$$\Pi_{D_1} = \pi(c-\theta x-e) - (1-\phi)[\pi(c-\theta x-\beta e) - \pi(c)] - K(e) - F. \tag{2}$$

In the second stage of the game, U and D_1 choose levels of investment to maximize their own profits. The equilibrium investments, which are denoted by $x(\phi)$ and $e(\phi)$, will be determined by the following first-order conditions

$$-\theta(1-\phi)\pi'(c-\theta x-\beta e) - G'(x) = 0, \tag{3}$$

$$-\pi'(c-\theta x-e) + \beta(1-\phi)\pi'(c-\theta x-\beta e) - K'(e) = 0. \tag{4}$$

To satisfy the second-order conditions of each firm's optimization problem and the stability requirements on reaction functions, we assume that

$$\frac{\partial^2\Pi_U}{\partial x^2} < 0, \frac{\partial^2\Pi_{D_1}}{\partial e^2} < 0, \frac{\partial^2\Pi_U}{\partial x^2}\frac{\partial^2\Pi_{D_1}}{\partial e^2} > \frac{\partial^2\Pi_U}{\partial e\partial x}\frac{\partial^2\Pi_{D_1}}{\partial x\partial e} \tag{5}$$

for any $x, e, \theta \geq 0$ and $\beta, \phi \in [0,1]$. These assumptions will be justified if $G(\cdot)$ and $K(\cdot)$ are sufficiently convex.

Before turning to the analysis of the first stage of the game, it is useful to know how an exogenous variation in the partial ownership level will influence the equilibrium investments. Totally differentiating Eqs. (3) and (4) with respect to ϕ, we find the following relationships.

Lemma 2. *If $\beta, \theta > 0$, $\phi < 1$, and $G(\cdot)$ and $K(\cdot)$ are sufficiently convex, we have that*

$$\frac{\partial x(\phi)}{\partial\phi} < 0 \quad \textit{and} \quad \frac{\partial e(\phi)}{\partial\phi} > 0.$$

Proof. Totally differentiating Eqs. (3) and (4) with respect to ϕ, we can get $\partial x(\phi)/\partial\phi = -\pi'(c-\theta x-\beta e)(\theta S_{22}+\beta S_{12})/(S_{11}S_{22}-S_{12}S_{21})$ and $\partial e(\phi)/\partial\phi = \pi'(c-\theta x-\beta e)(\beta S_{11}+\theta S_{21})/(S_{11}S_{22}-S_{12}S_{21})$, where $S_{11} = \theta^2(1-\phi)\pi''(c-\theta x-\beta e) - G''(x)$, $S_{12} = \beta\theta(1-\phi)\pi''(c-\theta x-\beta e)$, $S_{21} = \theta[\pi''(c-\theta x-e) - \beta(1-\phi)\pi''(c-\theta x-\beta e)]$, and $S_{22} = \pi''(c-\theta x-e) - \beta^2(1-\phi)\pi''(c-\theta x-\beta e) - K''(e)$. From the assumptions specified by Eq. (5), we know that $S_{11}S_{22}-S_{12}S_{21} > 0$. If $\beta, \theta > 0$ and $G(\cdot)$ and $K(\cdot)$ are sufficiently convex, we can further get $\beta S_{11}+\theta S_{21} = \theta^2\pi''(c-\theta x-e) - \beta G''(x) < 0$ and $\theta S_{22}+\beta S_{12} = \theta[\pi''(c-\theta x-e) - K''(e)] < 0$. Accordingly, $\partial x(\phi)/\partial\phi < 0$ and $\partial e(\phi)/\partial\phi > 0$. □

Lemma 2 tells us that, as the level of PEO increases, U's investment decreases while D_1's investment increases. The logic here is simple. As the level of PEO increases, U can capture a smaller fraction of the return from its own investment, and hence U's investment incentive decreases. Regarding D_1's investment, its return is in part captured by U because D_1's investment increases the value of the machine for D_2 through performance spillover, which in turn increases the price that D_1 must pay to purchase the machine through auction. But, as the level of PEO increases, D_1 can recover a larger fraction of the price increase as its own profit, and hence D_1's investment incentive increases.

How does the rate of performance spillovers affects D_1's investment incentives? To answer this question, we totally differentiate Eqs. (3) and (4) with respect to β and obtain the following lemma.

Lemma 3. *If $\beta, \theta > 0$, $\phi < 1$, and $G(\cdot)$ and $K(\cdot)$ are sufficiently convex, we have that*

$$\frac{\partial e(\phi)}{\partial \beta} < 0.$$

Proof. Totally differentiating Eqs. (3) and (4) with respect to β, we can get $\partial e(\phi)/\partial\beta = (1-\phi)[e\pi''(c-\theta x-\beta e)(\beta S_{11}+\theta S_{21}) - \pi'(c-\theta x-\beta e)S_{11}]/(S_{11}S_{22}-S_{12}S_{21})$, where $S_{11} = \theta^2(1-\phi)\pi''(c-\theta x-\beta e) - G''(x)$, $S_{12} = \beta\theta(1-\phi)\pi''(c-\theta x-\beta e)$, $S_{21} = \theta[\pi''(c-\theta x-e) - \beta(1-\phi)\pi''(c-\theta x-\beta e)]$, and $S_{22} = \pi''(c-\theta x-e) - \beta^2(1-\phi)\pi''(c-\theta x-\beta e) - K''(e)$. It is already known that $\pi'(\cdot) < 0$ and $\pi''(\cdot) > 0$. From Eq. (5), it is known that $S_{11} < 0$ and $S_{11}S_{22} - S_{12}S_{21} > 0$. If $\beta, \theta > 0$ and the innovative cost functions are sufficiently convex, we can further get $\beta S_{11} + \theta S_{21} = \theta^2\pi''(c-\theta x-e) - \beta G''(x) < 0$. Accordingly, if $\phi < 1$, it can be concluded that $\partial e(\phi)/\partial\beta < 0$. □

The intuition behind this conclusion is as follows. From Lemma 1, we known that D_1 wins the machine but the price paid is determined by D_2's willingness to pay. A rise in the performance spillover rate makes the machine more useful to D_2, which increases D_2's willingness to pay and then pushes up the price of the machine. A higher price of the machine means a smaller benefit D_1 can anticipate from its own investment. Accordingly, D_1's investment incentives will decline.

The first stage

In the first stage of the game, U and D_1 negotiate the level of PEO and the amount of monetary transfer through Nash bargaining. As outside options, U and D_1's profits without PEO can be expressed as

$$\bar{\Pi}_U = [\pi(c-\theta\bar{x}-\beta\bar{e}) - \pi(c)] - G(\bar{x}), \tag{6}$$

$$\bar{\Pi}_{D_1} = \pi(c-\theta\bar{x}-\bar{e}) - [\pi(c-\theta\bar{x}-\beta\bar{e}) - \pi(c)] - K(\bar{e}), \tag{7}$$

where $\bar{x} = x(0)$ and $\bar{e} = e(0)$. Combined with the profits with PEO, which are derived in the analysis of the second stage of the game, the equilibrium PEO level and the amount of monetary transfer will be determined by the following optimization problem

$$\begin{aligned}\max_{\phi,F} \quad & (\Pi_U - \bar{\Pi}_U)(\Pi_{D_1} - \bar{\Pi}_{D_1}) \\ \text{s.t.} \quad & \Pi_U \geq \bar{\Pi}_U, \Pi_{D_1} \geq \bar{\Pi}_{D_1} \end{aligned} \tag{8}$$

where $x = x(\phi)$ and $e = e(\phi)$. As a standard conclusion under Nash bargaining, for a certain ϕ, F will be chosen such that U and D_1 split the surplus from PEO equally. Given this, we can conclude that the optimal PEO level, which is denoted by ϕ^*, will be determined by

$$\max_{\phi} \Pi(\phi) = \pi(c - \theta x - e) - G(x) - K(e), \tag{9}$$

where $x = x(\phi)$ and $e = e(\phi)$.

Proposition 1 tells us that the equilibrium level of PEO is strictly positive when the performance spillover rate is sufficiently large.

Proposition 1. *There exists a $\bar{\beta} < 1$ such that $\phi^* > 0$ if $\beta > \bar{\beta}$.*

Proof. Differentiating the joint profit of U and D_1 with respect to ϕ, we can get the following first-order derivative, $\partial\Pi(\phi)/\partial\phi = [-\theta\pi'(c - \theta x - e) - G'(x)][\partial x(\beta, \theta, \phi)/\partial\phi] + [-\pi'(c - \theta x - e) - K'(e)][\partial e(\beta, \theta, \phi)/\partial\phi]$. From Eqs. (3) and (4), we know that $-\theta\pi'(c - \theta x - e) - G'(x) = \theta[(1-\phi)\pi'(c-\theta x-\beta e) - \pi'(c-\theta x-e)]$ and $-\pi'(c-\theta x-e) - K'(e) = -\beta(1-\phi)\pi'(c-\theta x-\beta e)$. Accordingly, the first-order derivative can be rewritten as $\partial\Pi(\phi)/\partial\phi = \theta[(1-\phi)\pi'(c-\theta x-\beta e) - \pi'(c-\theta x-e)][\partial x(\beta, \theta, \phi)/\partial\phi] - \beta(1-\phi)\pi'(c-\theta x-\beta e)[\partial e(\beta, \theta, \phi)/\partial\phi]$. Given Lemma 2, it can be concluded that $[\partial\Pi(\phi)/\partial\phi]_{\beta=1,\phi=0} = -\pi'(c - \theta x - e)[\partial e(\beta, \theta, \phi)/\partial\phi] > 0$. As $\partial\Pi(\phi)/\partial\phi$ is continuous with respect to β, there would exists a $\bar{\beta} < 1$ such that $[\partial\Pi(\phi)/\partial\phi]|_{\phi=0} > 0$ if $\beta > \bar{\beta}$. In other words, the equilibrium PEO level will be positive if the spillover rate is sufficiently large. □

To understand the logic behind Proposition 1, let us consider D_1's incentive to invest in e when $\phi = 0$. D_1's marginal stage 4 profit with respect to investment in e is $-\pi'(c - \theta x - e)$ (recall that $\pi'(\cdot)$ is negative). Hence, given x, the joint-profit maximizing level of e is given by

$$-\pi'(c - \theta x - e) - K'(e) = 0. \tag{10}$$

Should U's machine be used by D_2, D_1's investment in e increases D_2's profit due to performance spillovers. This means that D_1's investment in e increases the price D_1 must pay to U by $-\beta\pi'(c-\theta x-\beta e)$, which works in the direction of reducing D_1's investment in e. That is, given x, D_1 chooses e that solves

$$-\pi'(c - \theta x - e) + \beta\pi'(c - \theta x - \beta e) - K'(e) = 0. \tag{11}$$

The value of e satisfying (11) is smaller than the value of e satisfying (10) because $\pi''(\cdot) > 0$, indicating D_1's under-investment in e in the equilibrium. Notice that the under-investment gets severer as β increases.

PEO mitigates D_1's under-investment problem at the expense of U's under-investment. D_1's PEO in U increases D_1's investment incentive because it internalizes a part of the price that D_1 pays to U, but it reduces U's investment incentive because U can capture only $(1-\phi)$ fraction of the return from its own investment. This trade-off is clearly captured by first-order conditions (3) and (4). As the level of PEO, ϕ, increases, D_1's investment level gets closer to the joint-profit maximizing level because $-\pi'(c-\theta x-e)+\beta(1-\phi)\pi'(c-\theta x-\beta e)$ is increasing in ϕ, whereas U's investment gets further away from the joint-profit maximizing level because $-\theta(1-\phi)\pi'(c-\theta x-\beta e)$ is decreasing in ϕ. When β is sufficiently large, D_1's under-investment is sufficiently sever so that the positive effect of PEO dominates its negative effect at $\phi=0$. The result is that the equilibrium level of PEO is strictly positive under sufficiently large β.

Before closing the section, we compare investment levels in the stage 2 equilibrium, $x(\phi)$ and $e(\phi)$, to joint-profit maximizing levels, denoted x^J and e^J. Notice that (x^J, e^J) solves the following maximization problem.

$$\max_{x,e} \pi(c-\theta x-e)-G(x)-K(e); \tag{12}$$

Lemma 4 tells us that levels of U's and D_1's investments are both lower than joint-profit maximizing levels.

Lemma 4.

$$x(\phi) < x^J,\ e(\phi) < e^J.$$

Proof. It is known that the joint-profit maximizing investments, x^J and e^J, are determined by $m_1(x,e)=-\theta\pi'(c-\theta x-e)-G'(x)=0$ and $m_2(x,e)=-\pi'(c-\theta x-e)-K'(e)=0$ and the equilibrium investments, $x(\phi)$ and $e(\phi)$, are determined by $n_1(x,e)=-\theta(1-\phi)\pi'(c-\theta x-\beta e)-G'(x)=0$ and $n_2(x,e)=-\pi'(c-\theta x-e)+\beta(1-\phi)\pi'(c-\theta x-\beta e)-K'(e)=0$. To compare the equilibrium investments with the joint-profit maximizing investments, suppose that x' and e' are determined by $n_1(x,e)=-\theta(1-\phi)\pi'(c-\theta x-\beta e)-G'(x)=0$ and $m_2(x,e)=-\pi'(c-\theta x-e)-K'(e)=0$. It can be shown that $n_1(x^J,e^J)<0$ for $\beta<1$ or $\phi>0$. Supposing that there is an instantaneous adjustment process from (x^J,e^J) to (x',e'); then, given the stability requirements on the reactive functions, we can conclude that $x^J>x'$ and $e^J>e'$. As $n_2(x',e')<0$ for $\beta>0$ and $\phi<1$, the conclusion that $x'>x(\phi)$ and $e'>e(\phi)$ can be derived similarly. Accordingly, $x(\phi)<x^J$ and $e(\phi)<e^J$. □

5 Welfare consequences and policy implications

5.1 Welfare

Supposing that there is a representative consumer with utility function $U(q)+m$, where m is a numeraire good; then, the inverse demand function can be expressed as $p(q)=U'(q)$. It is natural to assume that the marginal utility is a declining function of q, i.e., $U''(q)<0$, which means $p'(q) = U''(q) < 0$. Under this inverse demand function, if a firm is the only producer of a final good and its marginal cost is c, the output decision will be made according to the following optimization problem

$$\max_q p(q)q - cq. \tag{13}$$

The corresponding first-order condition is

$$p(q) + p'(q)q - c = 0, \tag{14}$$

from which the optimal output level can be determined, denoted by $q(c)$. To satisfy the second-order condition, we assume that

$$2p'(q) + p''(q)q < 0. \tag{15}$$

Under this assumption, it can be shown that $q'(c) = 1/[2p'(q) + p''(q)q] < 0$. Based on Eqs. (13) and (14), the profit function in the case of optimal output can be expressed as

$$\pi(c) = -p'(q(c))[q(c)]^2. \tag{16}$$

It can be proved that $\pi'(c) = -q(c) < 0$ and $\pi''(c) = -q'(c) > 0$.

Under the profit function specified by Eq. (16), the first-order conditions of the second stage of the game, i.e., Eqs. (3) and (4), can be rewritten as

$$\begin{aligned} &\theta(1-\phi)q(c-\theta x-\beta e) - G'(x) = 0, \\ &q(c-\theta x - e) - \beta(1-\phi)q(c-\theta x-\beta e) - K'(e) = 0. \end{aligned} \tag{17}$$

Solving these two first-order conditions simultaneously, the equilibrium investments, $x(\phi)$ and $e(\phi)$, can be derived. In the first stage of the game, the level of PEO is chosen to maximize the joint profit of U and D_1, i.e.,

$$\max_\phi \Pi(\phi) = \pi(c-\theta x - e) - G(x) - K(e), \tag{18}$$

where $x = x(\phi)$ and $e = e(\phi)$. It is already known that the solution to this optimization problem is ϕ^*. As a comparison, suppose that, in the first stage of the game, ϕ is chosen to maximize social welfare; then, the optimal level of PEO would be determined by

$$\max_\phi W(\phi) = U(q) - (c-\theta x - e)q - G(x) - K(e), \tag{19}$$

where $q = q(c-\theta x - e)$, $x = x(\phi)$, and $e = e(\phi)$.[5] The solution to this optimization problem is denoted by ϕ^w. Comparing the socially optimal PEO level with the joint profit maximizing PEO level, the following relationship can be concluded.

[5]As there is no competition between D_1 and D_2 and there is only one machine which is sold to D_1, we assume that social welfare is the sum of the joint profit of U and D_1 and the surplus of the consumers of D_1.

Proposition 2. *$\phi^w > (=,<)\phi^*$ if $\beta G''(x) - \theta^2 K''(e) > (=,<)0$, where $x = x(\phi^*)$ and $e = e(\phi^*)$.*

Proof. As $\pi'(c_1) = -q(c_1)$, from Eq. (18), we can get $\Pi'(\phi) = [\theta q(c-\theta x-e)-G'(x)][\partial x(\phi)/\partial\phi]+[q(c-\theta x-e)-K'(e)][\partial e(\phi)/\partial\phi]$. As $U'(q) = p$, from Eq. (19), we can get $W'(\phi) = \Big([p(q)-(c-\theta x-e)][\partial q/\partial x]+\theta q-G'(x)\Big)[\partial x(\phi)/\partial\phi]+\Big([p(q)-(c-\theta x-e)][\partial q/\partial e]+q-K'(e)\Big)[\partial e(\phi)/\partial\phi]$, where $q = q(c-\theta x-e)$. Accordingly, $W'(\phi)-\Pi'(\phi) = -[p(q)-(c-\theta x-e)]q'\Big(\theta[\partial x(\phi)/\partial\phi]+[\partial e(\phi)/\partial\phi]\Big)$. As $p(q) - (c - \theta x - e) = -p'(q)q > 0$ and $q' < 0$, it can be concluded that

$$\text{sgn}\{W'(\phi) - \Pi'(\phi)\} = \text{sgn}\{\theta\frac{\partial x(\phi)}{\partial\phi} + \frac{\partial e(\phi)}{\partial\phi}\}.$$

Totally differentiating Eq. (17) with respect to ϕ, we can get $\theta[\partial x(\phi)/\partial\phi] + [\partial e(\phi)/\partial\phi] = [\beta G''(x)-\theta^2 K''(e)]q(c-\theta x-e)/(S_{11}S_{22}-S_{12}S_{21})$, where $S_{11} = -\theta^2(1-\phi)q'(c-\theta x-\beta e)-G''(x)$, $S_{12} = -\beta\theta(1-\phi)q'(c-\theta x-\beta e)$, $S_{21} = -\theta q'(c-\theta x-e)+\theta\beta(1-\phi)q'(c-\theta x-\beta e)$, and $S_{22} = -q'(c-\theta x-e)+\beta^2(1-\phi)q'(c-\theta x-\beta e)-K''(e)$. According to the assumption specified by Eq. (5), $S_{11}S_{22} - S_{12}S_{21} > 0$. That means

$$\text{sgn}\{\theta\frac{\partial x(\phi)}{\partial\phi} + \frac{\partial e(\phi)}{\partial\phi}\} = \text{sgn}\{\beta G''(x) - \theta^2 K''(e)\}.$$

To sum up, $\text{sgn}\{W'(\phi) - \Pi'(\phi)\} = \text{sgn}\{\beta G''(x) - \theta^2 K''(e)\}$. □

Proposition 2 tells us that the socially optimal level of PEO is higher than the equilibrium level of PEO when θ is small relative to β. This result is in contrast to the standard notion that PEO is anticompetitive and hence welfare reducing. The logic here can be explained as follows. Consider our base model with $\beta > \bar{\beta}$. In the equilibrium, U and D_1 choose $\phi = \phi^*$ (> 0) at stage 1 to maximize their joint profit. At stage 2, U and D_1 respectively choose x and e, and hence D_1's constant marginal cost becomes $c-\theta x-e \equiv c_1^*$. Lowering D_1's marginal cost increases not only U and D_1's joint profit but also consumer surplus, but U and D_1 ignore the effect on consumer surplus when they choose ϕ at stage 1. This implies that the equilibrium marginal cost c_1^* is higher than the socially optimal level.

We now consider a variant of the model in which a social planner chooses ϕ at stage 1 to maximize total surplus in the subsequent equilibrium. Let us consider the social planner's optimal choice $\phi = \phi^w$, using $\phi = \phi^*$ as a benchmark. As mentioned above, D_1's constant marginal cost corresponding to $\phi = \phi^*$, c_1^*, is higher than the socially optimal level.

How can the social planner reduce c_1 from c_1^*? Suppose that the social planner increases ϕ from $\phi = \phi^*$. An increase in ϕ reduces U's return from investing in x, resulting in a decrease in x. This works in the direction of increasing c_1, but this cost-increasing effect is relatively minor when θ is small. At the same time, an increase in ϕ increases e, working in the direction of reducing c_1. This is because D_1 pays the price $p = \pi(c-\theta x-\beta e) - \pi(c)$ to U at stage 3 and, as ϕ increases, D_1 internalizes a larger fraction of the price as its own profit. When ϕ increases by Δ, D_1's return from investing in e increases by $\Delta\pi(c-\theta x-\beta e)$. Observe that

D_1's marginal return of investing in e is $-\Delta\beta\pi'(c - \theta x - \beta e)$, which is increasing in β. Then, when β is relatively large, an increase in ϕ induces a larger increase in e, resulting in larger cost-reducing effect.

When θ is small relative to β, the social planner can decrease c_1 by increasing ϕ from $\phi = \phi^*$, because cost-increasing effect associated with x is dominated by cost-reduction effect associated with e. The socially optimal level of PEO is higher than its equilibrium level (that is, $\phi^w > \phi^*$) in this case. And, through an analogous logic, we have that $\phi^w < \phi^*$ when θ is large relative to β. This results in Proposition 2.

5.2 Policy implications

The difference between the socially optimal level of PEO and the equilibrium level of PEO provides a space for government intervention. For instance, a welfare maximizing social planner can announce an upper limit on the level of PEO, $\tilde{\phi}$, such that a potential PEO will be approved only if $\phi \leq \tilde{\phi}$. Given Proposition 2, the policy should be formulated as follows. When θ is small relative to β, the socially optimal level of PEO is higher than the equilibrium level and there is no need to impose any restrictions on PEO. In this case, the social planner can simply announce that $\tilde{\phi} = 1$. Whereas, when β is small relative to θ, the equilibrium level of PEO is too high from the standpoint of social planner. In this case, the maximum permissible level of PEO should be $\tilde{\phi} = \phi^w$.[6] To sum up, a welfare maximizing social planner may permit, partially permit, or prohibit (when $\phi^w = 0$) PEO, depending on the relative size of θ and β.

6 Endogenizing the rate of performance spillovers

The rate of performance spillovers, denoted by β, is a key element of our model, and the nature of our main results (Propositions 1 and 2) depends on β. In this section, we analyze an extension of our model in which the rate of performance spillovers is endogenously determined through the link between performance spillovers and asset specificity, and discuss robustness of our main results. Suppliers can often choose the degree of specificity of its asset. Mesquita, Anand, and Brush (2008), for example, points out that a supplier can choose the degree of dyad-specificity of its assets and capabilities, and, as the degree of dyad-specificity increases, the dyad partner buyer's teaching to the supplier becomes more effective for the supplier to serve the partner buyer, but less effective for the supplier to serve other buyers. This means in our framework that, as the upstream supplier U's asset is more tailored to the downstream manufacturer D_1's asset, D_1's knowledge transferred to U becomes more useful for D_1 but less useful for D_2.

In this extension, we assume that U chooses the degree of asset specificity $\alpha \in [1, 2]$ and once

[6]When $\phi^w < \phi^*$, we suggest that $\tilde{\phi} = \phi^w$. An underlying premise of this suggestion is that, in the range $[0, \phi^w]$, the first derivative of the joint profit ($\Pi(\phi)$) with respect to ϕ is always positive. It is difficult to verify this premise under the general demand function, but under linear demand it is true.

chosen the value of α becomes common knowledge. With this new element, the cost function of D_1 is modified to be $c - \theta x - \alpha e$ and that of D_2 becomes $c - \theta x - (2 - \alpha)e$. According to this setting, an increase in the level of asset specificity is reflected by a rise in α and, as the degree of asset specificity increases, D_1's teaching to U becomes more useful for D_1 but less useful for D_2. To determine the equilibrium degree of asset specificity, we consider a five-stage game, in which U chooses the degree of asset specificity $\alpha \in [1, 2]$ at stage 0. Other four stages are the same as stages 1 - 4 in the base model.

Before solving the game, to make things trackable, we make a simplification and assume that the downstream firms face a linear inverse demand function and the investment cost functions are quadratic. Specifically, $p = 1 - q$, $G(x) = \delta x^2/2$, and $K(e) = \delta e^2/2$, where p is the market-clearing price, q is the quantity of a downstream firm, and $\delta > 0$. In the previous analysis, we require that the investment cost functions are sufficiently convex. In the current context, it is equivalent to say that δ is sufficiently large. We maintain this assumption in the following analysis.

Given the above demand and cost structures, in stage 4, if D_1 buys the machine at price t, the profits of the three firms would be $\Pi_U = (1-\phi)t - \delta x^2/2 + F$, $\Pi_{D_1} = (1 - c + \theta x + \alpha e)^2/4 - (1-\phi)t - \delta e^2/2 - F$, and $\Pi_{D_2} = (1-c)^2/4$ and if D_2 buys the machine at price t, the profits of the three firms would be $\tilde{\Pi}_U = (1-\phi)t - \delta x^2/2 + F$, $\tilde{\Pi}_{D_1} = (1-c)^2/4 + \phi t - \delta e^2/2 - F$, and $\tilde{\Pi}_{D_2} = [1 - c + \theta x + (2-\alpha)e]^2/4 - t$. In stage 3, D_1 wins the machines and the price paid is $t = [1 - c + \theta x + (2-\alpha)e]^2/4 - (1-c)^2/4$. Then, by solving $\partial \Pi_U/\partial x = 0$ and $\partial \Pi_{D_1}/\partial e = 0$, the equilibrium investments in stage 2 can be derived

$$x(\alpha, \phi) = \frac{(1-c)(\delta - (\alpha-1)\alpha)\theta(1-\phi)}{2\delta^2 + (\alpha-1)\alpha\theta^2(1-\phi) + \delta(4(1-\alpha) - \theta^2 - ((2-\alpha)^2 - \theta^2)\phi)},$$
$$e(\alpha, \phi) = \frac{(1-c)\delta(\alpha(2-\phi) - 2(1-\phi))}{2\delta^2 + (\alpha-1)\alpha\theta^2(1-\phi) + \delta(4(1-\alpha) - \theta^2 - ((2-\alpha)^2 - \theta^2)\phi)}. \tag{20}$$

In stage 1, if PEO between U and D_1 occurs, the joint profit of involved firms can be expressed as

$$\Pi(\alpha, \phi) = \frac{(1 - c + \theta x + \alpha e)^2}{4} - \frac{\delta x^2}{2} - \frac{\delta e^2}{2}, \tag{21}$$

where $x = x(\alpha, \phi)$ and $e = e(\alpha, \phi)$. By solving $\partial \Pi(\alpha, \phi)/\partial \phi = 0$, the joint profit maximizing level of PEO can be derived

$$\phi(\alpha) = \frac{2(2-\alpha)^2((\alpha-1)\alpha - \delta)\delta - ((\alpha-1)\alpha^3 - 4\delta + 3(2-\alpha)\alpha\delta)\theta^2}{2(2-\alpha)^2((\alpha-1)\alpha - \delta)\delta + (\alpha^3 - \alpha^4 - 6\alpha\delta + 4\alpha^2\delta - 2(\delta-2)\delta)\theta^2}. \tag{22}$$

In stage 1, however, if PEO does not occur, the profit of U would be

$$\eta_U(\alpha) = \frac{(1 - c + \theta x + (2-\alpha)e)^2 - (1-c)^2 - 2\delta x^2}{4} \tag{23}$$

and the profit of D_1 would be

$$\eta_{D_1}(\alpha) = \frac{4e(\alpha - 1)(1 - c + \theta x + e) + (1-c)^2 - \delta e^2}{4}, \tag{24}$$

where $x = x(\alpha, 0)$ and $e = e(\alpha, 0)$. It can be proved that $\Pi(\alpha, \phi(\alpha)) > \eta_U(\alpha) + \eta_{D_1}(\alpha)$, which means that PEO is profitable and it occurs in equilibrium. Under Nash bargaining, the surplus from PEO is divided equally between U and D_1; then, U's equilibrium profit under PEO can be expressed as

$$\eta_U(\alpha) + \frac{\Pi(\alpha, \phi(\alpha)) - \eta_U(\alpha) - \eta_{D_1}(\alpha)}{2}. \tag{25}$$

In stage 0, U chooses the level of asset specificity to maximize its own profit. The optimal level of asset specificity, which is denoted by α^E, is determined according to the following first-order condition

$$\frac{\partial \Pi(\alpha, \phi(\alpha))}{\partial \alpha} + \frac{\partial \eta_U(\alpha)}{\partial \alpha} - \frac{\partial \eta_{D_1}(\alpha)}{\partial \alpha} = 0. \tag{26}$$

In order to characterize α^E, we need to specify the value of δ for algebraic tractability. In what follows, we let $\delta = 30$.[7] Then, the optimal level of asset specificity can be described in Figure 1.

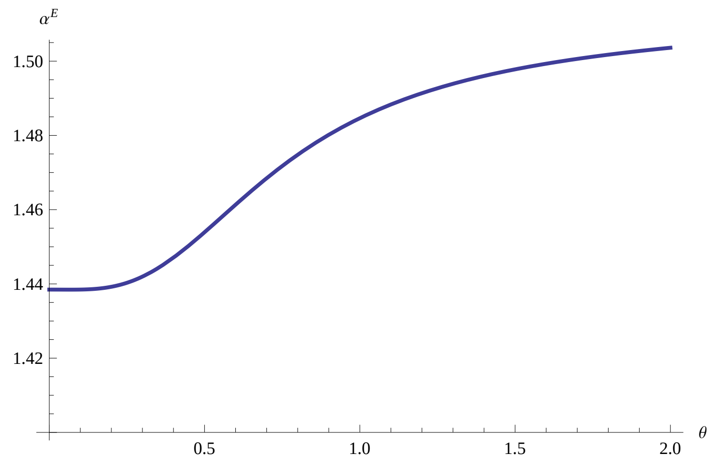

Figure 1

Figure 1 tells us that the optimal level of asset specificity is increasing in θ. The logic here can be explained as follows. When U chooses α at stage 0, it faces the following trade-off. On the one hand, higher α increases the value of U's output for D_1. This works in the direction of increasing the joint profit of D_1 and U, and hence higher α is beneficial for U.[8] On the other hand, higher α reduces the value of U's output for D_2, and hence reduces U's bargaining position when it bargains with D_1 over the monetary transfer at stage 1. This works in the direction of reducing U's profitability.[9] This trade-off is optimally balanced off at $\alpha = \alpha^E \in (1, 2)$.

Next, consider how θ affects α^E. An increase in θ increases the value of U's input for D_1, because D_1's marginal cost when it uses U's input is $c_1 = c - \theta x - \alpha e$. Due to the

[7] Using a different δ does not qualitatively change our following conclusions, which can be easily verified by using the above calculation process and its results.

[8] $\frac{\partial \Pi(\alpha, \phi(\alpha))}{\partial \alpha} > 0$.

[9] If α is not too small (for example $\alpha > 1.25$), we have $\frac{\partial \eta_U(\alpha)}{\partial \alpha} - \frac{\partial \eta_{D_1}(\alpha)}{\partial \alpha} < 0$.

complementarity between x and e, as θ increases, an increase in α more effectively increases U and D_1's joint profit.[10] Hence, higher θ increases U's benefit from increasing α.[11] The result is that α^E is increasing in θ. This implies that, when θ is small, the degree of U's asset specificity is also small.

In the previous section, we found that the socially optimal level of PEO is higher than its equilibrium level ($\phi^w > \phi^*$) when θ and the degree of asset specificity are both relatively small. Applying the analogous logic to this section's extension, one can conjecture that, when $\delta = 30$, $\phi^w > \phi^*$ holds when θ is relatively small. Keeping this conjecture in mind, in the remainder of this section we study the socially optimal level of PEO with endogenous formation of the level of asset specificity. To this end, we introduce a six-stage game

[**Stage 0**] The government proposes a PEO for U and D_1 with partial ownership level ϕ.

[**Stage 1**] U chooses the degree of asset specificity $\alpha \in [1, 2]$.

[**Stage 2**] U and D_1 accepts the partial ownership level proposed by the government and determine the corresponding monetary transfer through Nash bargaining.

[**Stage 3**] U and D_1 simultaneously and independently choose x and e.

[**Stage 4**] U sells the machine by auction.

[**Stage 5**] D_1 and D_2 choose some strategic variables and their profits realize.

This six-stage game is just a slight change of the previous five-stage game and there is no need to repeat the analysis of the last three stages. We solve this new game backwards starting from stage 2. Referring to the above analysis, for a certain level of PEO and a certain level of asset specificity, U's profit in stage 2 can be expressed as $\eta_U(\alpha) + [\Pi(\alpha, \phi) - \eta_U(\alpha) - \eta_{D_1}(\alpha)]/2$. In stage 1, U maximizes this profit by choosing α in the range $[1, 2]$. The optimal level of asset specificity is denoted by $\alpha(\phi)$. Then, in stage 0, the government's optimization problem can be expressed as follows

$$\max_{\phi} \quad W(\theta, \phi) = \frac{3(1 - c + \theta x + \alpha(\theta, \phi)e)^2}{8} - \frac{\delta x^2}{2} - \frac{\delta e^2}{2}, \tag{27}$$

where $x = x(\alpha(\phi), \phi)$ and $e = e(\alpha(\phi), \phi)$. When $\delta = 30$, the socially optimal level of PEO, which is denoted by ϕ^W, can be described in Figure 2.[12]

[10] Regarding complementarity, we mean that, when one kind of investment becomes more useful, the marginal benefit of the other kind of investment will increase.

[11] $\frac{\partial}{\partial \theta}[\frac{\partial \Pi(\alpha, \phi(\alpha))}{\partial \alpha}] > 0$.

[12] When θ is around 0.524, due to computational difficulty, it is hard to plot the exact curve of ϕ^W. To get around this problem, the curve near $\theta = 0.524$ is constructed by connecting some scattered points. And, these scattered points are obtained by numerical calculation.

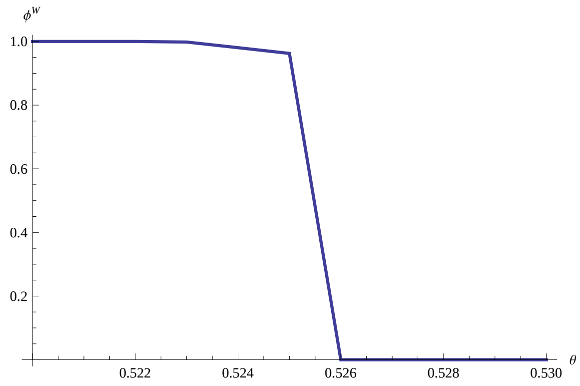

Figure 2

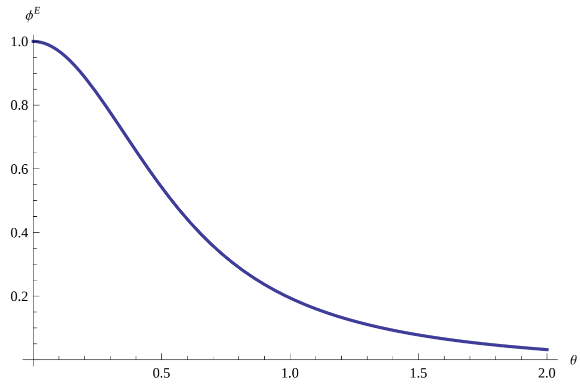

Figure 3

As a comparison, the equilibrium level of PEO $\phi^E = \phi(\alpha^E)$, is described in Figure 3. Accordingly, the following relationship can be derived.

Proposition 3. *There exists a* $\bar{\theta} \approx 0.525$ *such that* $\phi^W > (=,<)\phi^E$ *if* $\theta < (=,>)\bar{\theta}$.

It can be seen that, with endogenous level of asset specificity, the socially optimal level of PEO would be higher (lower) than the equilibrium level if θ is small (large). From Figure 1, it is known that the equilibrium level of asset specificity is low (high) if θ is small (large). And, a high (low) level of asset ownership means low (high) performance spillover rate. Accordingly, we can conclude that Proposition 2, which is derived under the assumption of exogenous performance spillovers, is robust.

7 Summary and conclusion

Transfer and spillovers of knowledge across firm boundaries are important determinants of firms' productivity in the knowledge economy. Downstream manufacturers often educate their upstream suppliers on the principles of advanced production systems, where suppliers can apply the acquired knowledge to serve other manufacturers. Performance spillovers, which are fundamentally different from information leakage, have attracted much less attention in the literature compared to information leakage despite their prevalence and significance. We have attempted to fill this gap in the literature by studying the role of PEO arrangement in mitigating the buyer's under-investment due to performance spillovers in vertical learning alliances. The downstream manufacturer's PEO in its partner supplier induces the manufacturer to transfer more knowledge to the supplier, but reduces the supplier's investment to improve its own productivity. We find that the equilibrium level of PEO is strictly positive when the performance spillover rate is sufficiently high and consequently D_1's under-investment problem is sufficiently severe. The equilibrium level of PEO can be lower than the socially optimal level, contrary to the standard intuition that PEO is anticompetitive and welfare reducing, and this finding has lead us to a new policy implication of PEO.

In order to simplify our analysis and focus on main insights, we have assumed away the downstream competition. Under the current model setting, performance spillovers raise the bargaining position of the supplier by increasing the machine's value in other applications, reducing the surplus a final product producer can anticipate from the vertical transaction. If we introduce downstream competition into the model, we conjecture that the relative bargaining position of the downstream producer will be further reduced. Accordingly, the under-investment problem will become more severe, which provides a even stronger justification for PEO arrangement as a cure to the problem. Such an extension of the model is left to a future research.

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