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Abstract: This paper deals with R&D investment and technology licensing in a supply chain formed of an original equipment manufacturer (OEM) and a contract manufacturer (CM). The R&D is conducted by the CM and the OEM agrees to pay a share of the cost. At the R&D stage, we assume that there are some uncertainties both in terms of performance of the developed technology and market uncertainties. These uncertainties are resolved in the sales stage, as technology matures and information about consumers' preferences become available. Further, the OEM can license the technology to a third party and share the revenues with the CM. We characterize equilibrium pricing and licensing strategies in two scenarios, namely, the licensing decision is made before or after the uncertainties are resolved. A comparison of the two equilibria indicates that the decision of licensing, that is, licensing or not, and its timing depend on the level of royalty from licensing and the share of each partner in these revenues. Interestingly, we obtain that for a large region of the parameter space, the two partners have the same preferences in terms of licensing. It is also found that different probability distribution of stochastic technology effectiveness results in different licensing strategies.

Keywords: Cooperative R&D, supply chains, technology licensing

Résumé : Cet article traite de l'investissement en R&D et de contrat de licence dans une chaîne d'approvisionnement formée d'un OEM (original equipment manufacturer) et d'un CM (contract manufacturer). La R&D est menée par le CM et l'OEM s'engage à payer une partie du coût. À l'étape de R&D, nous supposons qu'il existe des incertitudes tant sur le plan de la performance de la technologie développée que sur les incertitudes du marché. Ces incertitudes sont résolues à l'étape de commercialisation. L'OEM peut licencier la technologie à une autre firme et partager les revenus avec le CM. Nous caractérisons les stratégies d'équilibre et les stratégies d'octroi de la licence selon deux scénarios, à savoir, la décision d'octroi est prise avant ou après la résolution des incertitudes. Une comparaison des deux équilibres indique que la décision d'octroi de la licence, c'est-à-dire l'octroi de la licence ou non, et le moment d'octroi dépendent du niveau de redevance et de la part de chaque partenaire dans ces revenus. Fait intéressant, nous obtenons que, pour une grande région de l'espace de paramètres, les deux partenaires ont les mêmes préférences en termes d'octroi de la licence.

Mots clés : Coopération en R&D, chaînes d'approvisionnement, licence technologique

1 Introduction

Cooperation in research and development (R&D) is popular among technology-intensive firms pursuing time and cost reduction, better product design, and higher quality (Albino et al. (2007)). Coordinated investment in R&D is often preferred to competitive investment because: (i) it achieves higher economies of scale and scope; (ii) it reduces risk and wasteful duplication of R&D efforts; and (iii) it leads to higher total investments, and therefore higher knowledge, as appropriability and free riding are no more an issue (Harabi (2002), Ge and Hu (2008)).

Cooperation in R&D between firms can be horizontal or vertical. In the former, companies competing in the same product market coordinate their R&D efforts by, e.g., jointly investing in a research laboratory; see the seminal papers by d'Aspremont and Jacquemin (1988) and Kamien et al. (1992). Vertical cooperation refers to firms belonging to a supply chain, e.g., an upstream company and a downstream firm that collaborate in R&D to realize a collectively better outcome. For instance, Dell helped in 2002 its supplier Lexmark to enhance its printer technology with an innovative Dell-developed cartridge replenishment software, which eventually benefited both firms (Bhaskaran and Krishnan (2009)). Toyota Motor Co., Ltd has been cooperating with its suppliers to improve product performance since 1970.[1] Kisiel (2007) mentions that auto manufacturers have also been willing to involve suppliers during the production process, which allowed early detection of problems and the use of better components. Vonortas (1997) found that vertical cooperation dominated other cooperation types in the US during the period 1985-1995, a result also obtained by Arranz and de Arroyabe (2008).

In this paper, a downstream firm (an original equipment manufacturer, OEM) pays part of the R&D investment cost incurred by an upstream firm (a contract manufacturer, CM) to develop a new technology or a new product. This cost-sharing mechanism is in line with what has been observed empirically. For instance, General Motors Corporation provides an annual budget of 200-400 million dollars for its Six Sigma Program, with a significant portion of which being dedicated to improve its suppliers' component quality (Snee and Hoerl (2003)).

Additional to R&D cooperation, we assume that the OEM can license the new technology and share the revenues with the CM. Technology licensing means that an organization sells the rights to use its technology in the form of patents, processes and technical know-how to another firm for payment of royalties and/or other compensation (McDonald and Leahey (1985)). Technology licensing has for long been viewed by most high-tech enterprises as a quick and effective means for improving technology and innovation development (Fosfuri (2006), Benassi and Di Minin (2009), Lichtenthaler (2011), Zhao et al. (2014)). Arora et al. (2004) reports that over 15,000 licensing transactions in technology occurred worldwide already in the period 1985-1997 with a total value of over $320 billion. Technology licensing yields considerable additional revenues to firms, see, e.g., Kim and Vonortas (2006), Lichtenthaler (2011), Arora et al. (2013), Zhao et al. (2014).For instance, IBM, Texas Instruments and Dow Chemical are known to collect hundreds of millions of dollars in annual licensing revenues (Lichtenthaler (2011), Arora et al. (2013)). It also yields non-monetary benefits such as enabling the licensor to establish industry standards or enter new markets (Gambardella et al. (2007), Lichtenthaler (2011)). However, there may be a negative side to licensing as licensees can develop products that end up competing with the licensor's products (Fosfuri (2006), Kim (2009), Avagyan et al. (2014), Bagchi and Mukherjee (2014), Erkal and Minehart (2014)).To illustrate, the company RCA that once licensed its color TV technology to a number of Japanese companies for originally exclusive exploitation in Japan ended up facing competition in the U.S. market from these firms that quickly assimilated RCA's technology (Hill et al. (1990)). Consequently, the decision of licensing involves a trade-off between the revenues from licensing fees and the potential losses in sales revenues due to the competition from the licensee. Moreover, there is a dense literature that dealt with the design of licensing contracts, that is, the determination of fixed fees, royalties, and also about the coexistence of royalties and fixed fees; see, e.g., Rostoker (1984), Bagchi and Mukherjee (2014), Zhao et al. (2014), Savva and Taneri (2015). Crama et al. (2016) further investigated licensing contract in terms of three dimensions, namely, control rights, options and timing, and explored how an innovator should optimize the payment terms, the allocation of control rights and options, as well as the

[1] Toyota, 2012. New initiatives for quality improvement. http: //www. toyota-global. com/ company/ history-of-toyota/ 75years/ text/ entering-the-automotive-business/ chapter2/ section1/ item3. html

timing of the contracting decision. Introducing technology licensing into a closed-loop supply chain, that is, a manufacturer can license its technology to a remanufacturer, Hong et al. (2017) compared channel member's production, collection decisions and consumer surplus under fixed fee and royalty contracts. Huang and Wang (2017) also studied technology licensing issue in a closed-loop supply chain. Relative to the literature, our work simultaneously considers additional revenue and technology competition stemming from technology licensing based on a royalty contract. We regard technology licensing as a strategic decision for the firm to choose whether or not to license its technology to its rival.

Rewards from technology investment are far from being fully predictable (Ma et al. (2009), Bhaskaran and Krishnan (2009)). In the R&D stage, the firm cannot be sure to fully succeed in effectively designing and efficiently manufacturing new products. Additional to this technology (or performance) uncertainty, the firm faces market uncertainty as, at least initially, it does not have reliable data about consumer's preference and demand (Bacon et al. (1994), Bhattacharya et al. (1998)). These uncertainties are resolved in the sales stage as the firm has access to more accurate information and the market matures. Back to licensing, we shall consider two scenarios. In the first scenario, the OEM licensing decision has to be made before having the result of the R&D stage, and therefore we must account for both technology and market uncertainties. In the second scenario, we suppose that the OEM can delay its licensing decision till after the R&D stage and therefore only market uncertainty is relevant here.

The aim of this paper is to answer the following research questions:

1. What are the equilibrium strategies and outcomes in each licensing scenario?
2. In each scenario, under what conditions licensing is profitable to the OEM?
3. Under what conditions, the CM also benefits from licensing?

To address these questions, we consider a two-echelon supply chain playing a two-stage game, where an OEM and a CM jointly conduct technology investment to expand their market. The OEM makes the licensing decision and controls the share it pays of the CM's investment cost in R&D and its margin. The CM decides the investment level in R&D and its wholesale margin. This two-stage structure has also been adopted in, e.g., Xiao and Xu (2012) and Ge et al. (2014), however assuming away the above mentioned uncertainties and retaining different licensing and pricing contracts.

Two scenarios are considered for the timing of technology licensing, that is, in Stage 1 or in Stage 2. By determining and contrasting the strategies and outcomes in the two scenarios, we obtain the following insights: 1) If the technology licensing decision is made in Stage 1, there exists a threshold for the exogenous licensing fee, above which the OEM prefers to license the technology; otherwise, it does not license the technology. 2) If the technological uncertainty, or the technology competition intensity, is high, then the OEM does not license the technology. However, it does if its share in the licensing revenues is high. 3) If the licensing option is made in Stage 2, then no licensing will occur if the technology effectiveness is high, and the reverse if its low. 4) If the licensing fees are high (respectively low) and the revenue sharing rate is low (respectively high), then the OEM is better off licensing the technology in the first stage. However, if the licensing fees and the revenue sharing rate are both moderate, then the OEM prefers to make the licensing decision in the second stage, and the actual decision will depend on the technology effectiveness realizations. 5) Different probability distributions of the stochastic technology effectiveness lead to different technology licensing strategies.

The rest of the paper is organized as follows. Section 2 describes model development, then follows Section 3 and Section 3.2, which respectively present the equilibria of Scenario 1 and 2 where the technology licensing option occurs in Stage 1 and 2. Section 4 provides the optimal technology licensing strategy by comparing the solutions of scenarios. The numerical examples and managerial insights are provided in Section 4.1. This work is concluded in Section 5.

2 Model

Consider a two-stage game in a supply chain formed of an original equipment manufacturer and a contract manufacturer. In the first stage, the two players jointly invest in R&D to improve the OEM's product quality, which is sold in the market in the second stage. From now on, we shall use indifferently Stage 1 or *R&D stage* and Stage 2 or *sales stage*.

The outcome of R&D investment is uncertain both in terms of resulting technical performance and market acceptance (see, e.g., Bhattacharya et al. (1998), Oosterhuis et al. (2011)). As mentioned before, we assume that technology and market uncertainties are resolved in the sales stage, as the product's performance can be accurately tested by experts and consumers' defense groups, and the firm disposes of much better information about demand. Let the random variable Θ, following a two-point distribution, denote the stochastic technology effectiveness, with $P\{\Theta = \theta_2\} = \alpha, P\{\Theta = \theta_1\} = 1-\alpha$ and $0 \leq \theta_1 < \theta_2 \leq 1, 0 \leq \alpha \leq 1$. The corresponding mean and variance are $\mu = \alpha\theta_2 + (1-\alpha)\theta_1$ and $\sigma^2 = \alpha(1-\alpha)(\theta_2 - \theta_1)^2$, respectively.

Denote by x the R&D activities and suppose that the cost is convex increasing and well approximated by the following simple quadratic function:

$$C(x) = x^2,$$

which is commonly used in the literature to characterize diminishing returns from investment (e.g., d'Aspremont and Jacquemin (1988)). We assume that this total cost is shared between the two partners, with the OEM picking up a share ϕ and the CM the remaining $1-\phi$.

Denote by m the OEM's margin and by w the CM's wholesale margin. The retail price to consumer is then given by $p = m + w$. We suppose that the demand is decreasing in the retail price p, and increasing in the technology quality,[2] which is measured by Θx. If the OEM licenses the technology to another supplier operating in the same market, then it gets some revenues from the licensee, and loses some demand to it. Let Λ be the indicator function characterizing the technology licensing decision, that is,

$$\Lambda = \begin{cases} 1, & \text{licensing,} \\ 0, & \text{no licensing.} \end{cases} \tag{1}$$

The supply chain's revenue from licensing is royalty based and given by $\pi\Lambda\Theta x$, where π is the royalty. Rostoker (1984) reports that 39% of licensing cases are based on royalty contract alone, 13% are fixed-fee alone, and 46% combines royalty and fixed-fee together. The total licensing revenue is shared between the supply chain's members, with the OEM getting the exogenously given percentage τ and the CM the rest, i.e., $1-\tau$. This revenue sharing mechanism is widely used in supply chains, see, e.g., Cachon and Lariviere (2005), and in particular in the Dell-Lexmark example mentioned in the introduction.

On the negative side of licensing, some consumers will buy from the licensee instead of purchasing the product from the CM. To measure this loss, denote by M the market potential in the absence of any technology investment. By conducting R&D, the supply chain expects to increase this market potential by $\vartheta\Theta x$, where ϑ is a nonnegative scaling parameter. Denote by δ the supplier substitution rate $(0 < \delta < 1)$ such that the licensee's sales could be measured by $\delta\vartheta\Lambda\Theta x$. Consequently, the market size is given by $M + \vartheta\Theta x - \delta\vartheta\Lambda\Theta x$. To keep the model parsimonious, we normalize from now on M and ϑ to one (Shum et al. (2016)). We assume the demand function to be linear, which is common in the economics and management science literature and given by

$$D = 1 + \Theta x\,(1 - \delta\Lambda) - (m + w). \tag{2}$$

Note that in the above equation, the marginal impact of retail price on demand has been normalized to one. Further, without any loss of generality, we normalize the unit production cost to zero.

Assuming profit maximization behavior, the objective functions of the OEM and CM are then given by

$$\Pi_o = mD + \tau\pi\Lambda\Theta x - \phi x^2, \tag{3}$$

[2] We use indifferently the terms technology quality, product performance and (simply) product's quality.

$$\Pi_c = wD + (1-\tau)\pi\Lambda\Theta x - (1-\phi)x^2. \tag{4}$$

We formulate the problem as a two-stage game, with each stage being played à la Stackelberg with the OEM acting as leader and the CM as follower.

Remark 1 *In the supply chain and marketing channels literature, the typical assumption is that the manufacturer determines first its wholesale price and next the retailer announces its retail price (see, e.g., the survey in Ingene et al. (2012)). Still, the sequence can be reversed for some reasons, e.g., a powerful retailer. Here, we have in mind the example of cooperation between Apple (the OEM) and Foxconn (the CM). Apple plays as a leader and decides the quality and retail price of products, and Foxconn, as the follower, is responsible of assembling mobile phones according to Apple's request, and charges the wholesale price of component.*

A formal description of the two scenarios follows.

Licensing decision in Stage 1: In this scenario, the optimization problems in the two stages are defined as follows:

Stage 1: The OEM announces licensing decision (Λ) and investment cost sharing rate ϕ. The CM then determines technology investment x. Each player maximizes its individual expected profits, that is,

$$\begin{aligned} &\max_{\Lambda,\phi}\ E[\Pi_o] = E[mD + \tau\pi\Lambda\Theta x - \phi x^2], \\ &\max_{x}\ E[\Pi_c] = E[wD + (1-\tau)\pi\Lambda\Theta x - (1-\phi)x^2]. \end{aligned} \tag{5}$$

Stage 2: The technology effectiveness realizes as θ_2 with probability α and θ_1 with probability $1-\alpha$. Knowing this, the OEM determines first its retail margin m, and next the CM sets its wholesale price w. The optimization problems are given by

$$\begin{aligned} &\max_{m}\ \Pi_o = md + \tau\pi\Lambda\theta x - \phi x^2, \\ &\max_{w}\ \Pi_c = wd + (1-\tau)\pi\Lambda\theta x - (1-\phi)x^2, \end{aligned} \tag{6}$$

where θ and d denote the realization of the stochastic process and the demand, respectively.

Licensing decision in Stage 2: In this scenario, the optimization problems in the two stages are defined as follows:

Stage 1: The OEM decides cost sharing rate ϕ, and the CM sets technology investment x afterwards. The optimization problems are

$$\begin{aligned} &\max_{\phi}\ E[\Pi_o] = E[mD + \tau\pi\Lambda\Theta x - \phi x^2], \\ &\max_{x}\ E[\Pi_c] = E[wD + (1-\tau)\pi\Lambda\Theta x - (1-\phi)x^2]. \end{aligned} \tag{7}$$

Stage 2: The technology effectiveness realizes as θ_2 with probability α and θ_1 with probability $1-\alpha$. Then, the OEM decides whether or not to license the technology, i.e., chooses Λ, and the retail margin m. The CM next determines the wholesale price w. The optimization problems are given by

$$\begin{aligned} &\max_{\Lambda,m}\ \Pi_o = md + \tau\pi\Lambda\theta x - \phi x^2, \\ &\max_{w}\ \Pi_c = wd + (1-\tau)\pi\Lambda\theta x - (1-\phi)x^2. \end{aligned} \tag{8}$$

To save on notation, we introduce the auxiliary variable

$$\xi := \mu^2 + \sigma^2 = \alpha\theta_2^2 + (1-\alpha)\theta_1^2.$$

Note that under our assumption $0 \le \theta_1 < \theta_2 \le 1$, we clearly have $\xi \le 1$.

3 Equilibria

In this section, we characterize the equilibria in both scenarios. For each of them, we verify under what conditions licensing is optimal to the OEM and eventually if this suits the CM.

3.1 Licensing decision in stage 1

The following proposition characterizes the subgame-perfect equilibrium strategies and outcomes for a given Λ:

Proposition 1 *Assuming an interior solution and if the technology licensing option is made in Stage 1, then the equilibrium strategies for a given* Λ *are given by*

$$\phi = \frac{8\Lambda\pi\big(\xi(5-7\tau)(1-\delta\Lambda)^2-16(1-3\tau)\big)+(1-\delta\Lambda)\big(\xi(1-\delta\Lambda)^2+48\big)}{16\big(5(1-\delta\Lambda)+8\Lambda\pi(1+\tau)\big)}, \tag{9}$$

$$x = \frac{\mu\big(5(1-\delta\Lambda)+8\Lambda\pi(1+\tau)\big)}{2(16-3\xi(1-\delta\Lambda)^2)}, \tag{10}$$

$$m = \frac{8\Lambda\mu\theta\pi(1+\tau)(1-\delta\Lambda)+(5\mu\theta-6\xi)(1-\delta\Lambda)^2+32}{4(16-3\xi(1-\delta\Lambda)^2)}, \tag{11}$$

$$w = \frac{8\Lambda\mu\theta\pi(1+\tau)(1-\delta\Lambda)+(5\mu\theta-6\xi)(1-\delta\Lambda)^2+32}{8(16-3\xi(1-\delta\Lambda)^2)}, \tag{12}$$

and the expected profits by

$$E[\Pi_o] = \frac{16\Lambda\pi\mu^2(1+\tau)\big(5(1-\delta\Lambda)+4\Lambda\pi(1+\tau)\big)+(25\mu^2-24\xi)(1-\delta\Lambda)^2+128}{64(16-3\xi(1-\delta\Lambda)^2)}, \tag{13}$$

$$E[\Pi_c] = \frac{16\Lambda\pi\mu^2\big((3-2\tau)(1-\delta\Lambda)+4\Lambda\pi(1-\tau^2)\big)+(5\mu^2-6\xi)(1-\delta\Lambda)^2+32}{32(16-3\xi(1-\delta\Lambda)^2)}. \tag{14}$$

Proof. See Appendix. □

The results in the above proposition call for the following comments. First, the proposition is stated under the assumption of an interior solution, that is, $0 < \phi < 1$, and $x, m, w > 0$. It is straightforward to verify that x, m and w are strictly positive. For $\Lambda = 0$, we have

$$\phi_{\Lambda=0} = \frac{\xi+48}{80},$$

which clearly shows that $0 < \phi_{\Lambda=0} < 1$. For $\Lambda = 1$, it is again easy to verify that $\phi < 1$ for all parameter values. However, the following restriction is needed to have a positive ϕ :

$$\text{if } A = \xi(5-7\tau)(1-\delta)^2 - 16(1-3\tau) < 0, \text{ then } \pi < -\frac{1}{8A}(1-\delta)(\xi(1-\delta)+48).$$

The above condition states that for the share of the OEM in the technology investment cost to be positive, the license fee must not be too high.

Second, we observe that the leader's margin is twice the follower's margin, that is, $m = 2w$. This result is classical in the marketing channels literature, see, e.g., Ingene et al. (2012), Martín-Herrán and Taboubi (2015). Finally, a sensitivity analysis of strategies and expected payoffs leads to the results in Table 1. The computational details are in the Appendix.

Table 1 shows that all equilibrium strategies increase with π, τ, μ and σ^2 except the cost-sharing rate ϕ. Specifically, ϕ is increasing in τ, but its variations are ambiguous with respect to π, μ and σ^2. Intuitively, higher technology investment leads to higher market size, which in turn allows for a high retail price. On the other hand, the larger the royalty π or the share of licensing revenues τ that the OEM keeps, the larger the incentive to invest in R&D. High mean μ and variance σ^2 attract more technology investment, enabling

Table 1: Sensitivity analysis in scenario 1

	π	τ	μ	σ^2
ϕ	?	+	?	?
x	+	+	+	+
m	+	+	+	+
w	+	+	+	+
$E[\Pi_o]$	+	+	+	+
$E[\Pi_c]$	+	-	+	+

the channel members to set a high retail margin and wholesale price. The derivative of ϕ with respect to π (see Appendix) indicates that ϕ increases in π if $\tau > \frac{2}{3}$, otherwise, it decreases with π. This implies that the licensing revenue sharing must be large enough ($\tau > \frac{2}{3}$) for the OEM to benefit from a high licensing margin; otherwise, it suffers from. Additionally, as seen from the derivatives of ϕ with respect to μ and σ^2 (see Appendix) that if $\tau < \frac{5}{7}$, ϕ increases with μ and σ^2, otherwise, ϕ may decrease with μ and σ^2. Facing a relatively low revenue sharing rate ($\tau < \frac{5}{7}$), the OEM still prefers to share more cost to boost CM's investment because this behavior may generate more demand and eventually profit for OEM. On the contrary, with a high enough revenue rate, i.e., $\tau > \frac{5}{7}$, although large investment is generated by high mean and variance, the corresponding cost increases fast, and therefore the OEM reduces the cost sharing rate to avoid this high cost. Table 1 also shows that the expected profit of OEM is positively impacted by π, τ, μ and σ^2, while CM's expected profit experiences a positive effect of π, μ and σ^2 and a negative one from τ. Both channel members profit from a high royalty, and it is natural that the OEM is better off with a high revenue sharing, but the CM is worse off. Mean and variance lift up the profits of OEM and CM, indicating that great uncertainty in technology effectiveness benefits both channel members.

Comparing the expected profits with and without technology licensing yields the OEM's technology licensing strategy.

Proposition 2 *When made in the first stage, the equilibrium technology licensing strategy is defined by*

$$\Lambda = \begin{cases} 1, & \pi \geq \bar{\pi}, \\ 0, & \pi < \bar{\pi}, \end{cases} \tag{15}$$

where

$$\sqrt{9\xi^2(1-\delta)^2 - 48\xi(\delta^2-2\delta+2)+256}$$

$$\sqrt{(3\xi(1-\delta)-16)^2 - 48\xi}$$

$$\bar{\pi}_o = \frac{5\sqrt{9\xi^2(1-\delta)^2 - 48\xi(\delta^2-2\delta+2)+256} - (16-3\xi)(1-\delta)}{8(16-3\xi)(1+\tau)}. \tag{16}$$

Proof. Use (13) to compute

$$E[\Pi_o, \Lambda = 1] - E[\Pi_o, \Lambda = 0] = \frac{16\Lambda\pi\mu^2(1+\tau)\big(5(1-\delta)+4\pi(1+\tau)\big)+(25\mu^2-24\xi)(1-\delta)^2+128}{64(16-3\xi(1-\delta)^2)} - \frac{(25\mu^2-24\xi)+128}{64(16-3\xi)}.$$

It is straightforward to verify that

$$E[\Pi_o, \Lambda = 1] - E[\Pi_o, \Lambda = 0] \geq 0 \Leftrightarrow \pi \geq \bar{\pi}_o.$$

□

The above proposition shows, not unexpectedly, that the decision of licensing depends on all parameter values. In short, the main message is that licensing requires a sufficiently high value of π to offset the profit losses from the decreased demand for the OEM when it opts for licensing. Note that $\bar{\pi}_o$ is upper-bounded by $\frac{4+\delta}{8(1+\tau)}$. Indeed,

$$\begin{aligned}\bar{\pi}_o &= \frac{5\sqrt{9\xi^2(1-\delta)^2-48\xi(\delta^2-2\delta+2)+256}-(16-3\xi)(1-\delta)}{8(16-3\xi)(1+\tau)}\\ &< \frac{5\sqrt{9\xi^2-48\xi+256}-(16-3\xi)(1-\delta)}{8(16-3\xi)(1+\tau)}\\ &= \frac{5\sqrt{(16-3\xi)^2}-(16-3\xi)(1-\delta)}{8(16-3\xi)(1+\tau)} = \frac{4+\delta}{8(1+\tau)}.\end{aligned}$$

Further, the threshold $\bar{\pi}_o$ increases in mean μ, variance σ^2, and competition intensity δ, but decreases in revenue sharing rate τ. The increase in μ and σ^2 means that higher technology efficiency and volatility are deterrent for licensing. One interpretation is that high mean and variance greatly pull up investment, and then demand, but it may lead to a large demand losses if the OEM licenses the technology. The corresponding profit losses may not be offset by the external revenue from licensing. As such, the OEM gives up licensing. The comparative static analysis of $\bar{\pi}_o$ with respect to τ, δ shows that the licensing region enlarges with τ and shrinks with δ. Clearly, high external revenue drives the OEM to choose licensing, and extensive technology competition damages the OEM's initiative towards licensing.

3.2 Licensing decision in Stage 2

As in the previous scenario, we start by solving the second-stage problem in (8). Recall that in this scenario, the technology effectiveness is θ_2 with probability α and θ_1 with probability $1-\alpha$. Next, the OEM decides whether to license the technology, i.e., chooses Λ, and the retail margin m. After that the CM determines the wholesale price w. The following lemma characterizes the second-stage equilibrium.

Lemma 1 *If the technology licensing decision is made in Stage 2, then the equilibrium strategies are as follows:*

$$\Lambda^* = \begin{cases} 1, & x < \bar{x}, \\ 0, & x \geq \bar{x}, \end{cases} \tag{17}$$

$$m^*(\theta) = \begin{cases} \frac{1}{2}\left(\theta x(1-\delta)+1\right), & x < \bar{x}, \\ \frac{1}{2}\left(\theta x+1\right), & x \geq \bar{x}, \end{cases} \tag{18}$$

$$w^*(\theta) = \begin{cases} \frac{1}{4}\left(\theta x(1-\delta)+1\right), & x < \bar{x}, \\ \frac{1}{4}\left(\theta x+1\right), & x \geq \bar{x}, \end{cases} \tag{19}$$

where

$$\bar{x} = \frac{2(4\tau\pi-\delta)}{\delta\theta(2-\delta)}.$$

Proof. See Appendix. □

Lemma 1 shows that the technology licensing option is contingent to the investment decision x made in the first stage. The Lemma shows that if x is larger than a threshold $\bar{x}$, which we assume to be positive, i.e., $4\tau\pi > \delta$, then the OEM would not license the technology. One way of summarizing the result regarding the licensing decision is by stating that the OEM will license a technology that does not require a high investment. Note that the threshold is increasing in the revenue sharing rate τ and in the marginal licensing revenue π, but is decreasing in the competition intensity δ and in the stochastic technology effectiveness. Additionally, the licensing region when $\Theta = \theta_2$ is smaller than when $\Theta = \theta_1$, that is, the higher the technology efficiency, the smaller is the licensing region. Further, as in the previous scenario, the equilibrium retail margin is twice the wholesale price. However, as expected, these strategies depend here on the realization of the stochastic process and not on its statistics.

The first stage is played sequentially, with the OEM (the leader) announcing first the investment sharing rate ϕ and next the CM (the follower) decides on the investment x. As usual, we start by first determining the follower's reaction function. Given the OEM's investment sharing rate ϕ, and taking the second-stage responses into account, the CM's problem is to determine the technology investment x to maximize its expected profit, that is,

$$\max_{x} \; E[\Pi_{c_1}] = E[w^*(\Theta)D + (1-\tau)\pi\Lambda^*\Theta x - (1-\phi)x^2]. \tag{20}$$

Accounting for the results in the second stage, the above expected payoff can then be rewritten as follows:

$$E[\Pi_{c_1}] = \begin{cases} \frac{1}{16}\xi x^2(1-\delta)^2 + \frac{1}{8}\mu x(1-\delta) \\ +\pi\mu x(1-\tau) - (1-\phi)x^2 + \frac{1}{16}, & x < \frac{2(4\tau\pi-\delta)}{\delta\theta_2(2-\delta)}, \\ \\ \frac{\alpha}{16}\left(\theta_2 x+1\right)^2 - (1-\phi)x^2 \\ +(1-\alpha)\left(\frac{1}{16}\left(\theta_1 x(1-\delta)+1\right)^2 + \pi\theta_1 x(1-\tau)\right), & \frac{2(4\tau\pi-\delta)}{\delta\theta_2(2-\delta)} \le x \le \frac{2(4\tau\pi-\delta)}{\delta\theta_1(2-\delta)}, \\ \\ \frac{1}{16}\xi x^2 + \frac{1}{8}\mu x - (1-\phi)x^2 + \frac{1}{16}, & x > \frac{2(4\tau\pi-\delta)}{\delta\theta_1(2-\delta)}. \end{cases} \tag{21}$$

The CM's first-stage investment response is given below by solving the optimization problem (20).

Lemma 2 *The CM's first-stage best investment response is*

$$x^* = \begin{cases} \frac{\mu(8\pi(1-\tau)+1-\delta)}{16(1-\phi)-\xi(1-\delta)^2}, & 0 < \phi < \phi_1, \\ \frac{\theta_1(1-\alpha)(1-\delta)+8\pi\theta_1(1-\tau)(1-\alpha)+\alpha\theta_2}{16(1-\phi)-\theta_1^2(1-\alpha)(1-\delta)^2-\alpha\theta_2^2}, & \phi_1 \le \phi \le \phi_2, \\ \frac{\mu}{16(1-\phi)-\xi}, & \phi_2 < \phi < 1, \end{cases} \tag{22}$$

where

$$\phi_1 = 1 - \frac{1}{32(4\tau\pi-\delta)}\Big(\delta\theta_1\theta_2(1-\alpha)(2-\delta)\big(8\pi(1-\tau)+1-\delta\big) + 2(1-\alpha)\theta_1^2(1-\delta)^2\big(4\tau\pi-\delta\big) + \alpha\theta_2^2(8\tau\pi-\delta^2)\Big),$$
$$\phi_2 = 1 - \frac{\delta\mu\theta_1(2-\delta)+2\xi(4\tau\pi-\delta)}{32(4\tau\pi-\delta)}.$$

Proof. See Appendix. □

Lemma 2 shows that the investment in R&D has three different values depending on some range values of ϕ. Moreover, if there is a low or high cost-sharing rate, i.e., $0 < \phi < \phi_1$ or $\phi_2 < \phi < 1$, the optimal investment depends on the mean and variance. Specifically, it increases with μ and σ^2. When the cost-sharing rate is moderate, that is, $\phi_1 \le \phi \le \phi_2$, then the investment depends on the realizations θ_1, θ_2, and is increasing on both of them.

Incorporating the CM's best responses given in Lemma 2 in the OEM's objective function, we then need to solve the following optimization problem:

$$\max_{\phi} \; E[\Pi_{o_1}] = E[m^*(\Theta)D + \tau\pi\Lambda^*\Theta x^* - \phi x^{*2}], \tag{23}$$

where

$$E[\Pi_{o_1}] = \begin{cases} \frac{16\pi\mu^2(1+\tau)(5(1-\delta)+4\pi(1+\tau))+(25\mu^2-24\xi)(1-\delta)^2+128}{64(16-3\xi(1-\delta\eta)^2)}, & 0<\phi<\phi_1, \\ \frac{\alpha}{8k_2^2}((k_1\theta_2+k_2)^2-8\phi k_1^2)+\frac{1-\alpha}{8k_2^2}\Big(((1-\delta)\theta k_1+k_2\Big)^2 & \\ +8\tau\pi\theta_1 k_1 k_2 - 8\phi k_1^2\Big), & \phi_1 \le \phi \le \phi_2, \\ \frac{25\mu^2-24\xi+128}{64(16-3\xi)}, & \phi_2<\phi<1, \end{cases} \tag{24}$$

and

$$\begin{aligned} k_1 &= (1-\alpha)\theta_1(8\pi(1-\tau)-\delta)+(1-\alpha)\theta_1+\alpha\theta_2, \\ k_2 &= 16(1-\phi)-\alpha\theta_2^2-(1-\alpha)(1-\delta)^2\theta_1^2. \end{aligned}$$

Solving the OEM's optimization problem in (23) yields the following first-stage optimal solution.

Proposition 3 *The OEM's first-stage optimal investment cost sharing rate is given by*

$$\phi^* = \begin{cases} \frac{\xi}{80}+\frac{6}{10}, & \pi<\pi_2, \\ \frac{(1-\alpha)(1-\delta)^2\theta_1^2(k_3\theta_1(1-\alpha)-\alpha\theta_2)+k_4+\alpha\theta_2(k_3\theta_1\theta_2(1-\alpha)-\alpha\theta_2^2-48)}{5\theta_1(1-\alpha)(1-\delta)+5\alpha\theta_2+8\eta\theta_1\pi(1-\alpha)(1+\tau)}, & \pi_2\le\pi\le\pi_1, \\ \frac{8\pi\Big(\xi(5-7\tau)(1-\delta)^2-16(1-3\tau)\Big)+(1-\delta)\Big(\xi(1-\delta)^2+48\Big)}{16\Big(5(1-\delta)+8\pi(1+\tau)\Big)}, & \pi_1<\pi. \end{cases} \tag{25}$$

where

$$k_3 = 8\pi(7\tau-5)-(1-\delta),$$

$$k_4 = 16\theta_1(1-\alpha)(8\pi(1-3\tau)-3(1-\delta)),$$

$$\pi_1 = \frac{\delta(5\mu\theta_2(1-\delta)(2-\delta)-12\xi(1-\delta)^2+64)}{8(32\tau-6\xi\tau(1-\delta)^2-\mu\theta_2\delta(2-\delta)(1+\tau))}, \tag{26}$$

$$\pi_2 = \frac{\delta(5\mu\theta_1(2-\delta)+64-12\xi)}{16\tau(16-3\xi)}. \tag{27}$$

Proof. See Appendix. □

Proposition 3 shows that if the revenue margin from licensing is sufficiently low, i.e., $\pi<\pi_2$, then the equilibrium cost-sharing rate is the same than the one obtained in Scenario 1 without licensing, and it is always strictly larger than 0.6. If π is high enough, that is, $\pi>\pi_1$, then the equilibrium cost-sharing rate corresponds to the one in Scenario 1 with licensing. When the external margin is moderate, that is, $\pi_2\le\pi\le\pi_1$, then the equilibrium cost-sharing rate depends on the realizations θ_1 and θ_2.

4 Comparison of the two scenarios

In this section, we compare the equilibrium payoffs obtained in the two scenarios. Since the decision of licensing is taken by the OEM and it is the leader of the game, we first check when licensing is profitable to the OEM. Second, we see if the made decision suits the CM or not, keeping in mind that, as a follower, it cannot change it. As one could easily expect, the results depend on the parameter values and could be presented in different ways. However, the believe that the most comprehensive approach is to focus on the royalty parameter π. We have already defined three threshold values, namely, $\bar{\pi}_o, \pi_1, \pi_2$ in (16), (26) and (27), respectively. Further, we introduce the following thresholds for the OEM

$$\begin{aligned} \widetilde{\pi}_o &: \text{ value such that } E[\Pi_o, \Lambda=1] = E[\Pi_o^*], \\ \widehat{\pi}_o &: \text{ value such that } E[\Pi_o, \Lambda=0] = E[\Pi_o^*], \end{aligned}$$

and the following values for the CM:

$$\bar{\pi}_c = \frac{1}{8(16-3\xi)(1-\tau^2)}\left((16-3\xi)(1-\delta)(2\tau-3)+\sqrt{A_1+A_2-A_3}\right),$$
$$\widetilde{\pi}_c \ : \ \text{value such that } E[\Pi_c, \Lambda = 1] = E[\Pi_c^*],$$
$$\widehat{\pi}_c \ : \ \text{value such that } E[\Pi_c, \Lambda = 0] = E[\Pi_c^*],$$

where

$$A_1 = 3(1-\delta)^2(3\xi^2(2\tau-3)^2+128\tau(3\xi-8)),$$
$$A_2 = 16\delta(2-\delta)(3\tau^2(13\xi-48)+39\xi-64),$$
$$A_3 = 32(3\xi-8)(9+4\tau^2).$$

The following proposition characterizes the conditions under which the OEM licenses or not the technology and the decision stage.

Proposition 4 *The optimal technology licensing strategy depends on external revenue margin as follows:*

R1: *If $\bar{\pi}_o < \pi < \pi_2$, or $\pi > \max\{\pi_1, \bar{\pi}_o\}$, then the OEM licenses its technology, and there is no difference if this decision is made in Stage 1 or 2.*

R2: *If $\pi < \min\{\pi_2, \bar{\pi}_o\}$, or $\pi_1 < \pi < \bar{\pi}_o$, then the OEM does not license its technology, and there is no difference if this decision is made in Stage 1 or 2.*

R3: *If $\max\{\pi_2, \widetilde{\pi}_o\} < \pi < \pi_1$, then the OEM licenses its technology in Stage 1.*

R4: *If $\max\{\pi_2, \widehat{\pi}_o\} < \pi < \min\{\pi_1, \widetilde{\pi}_o\}$,then the licensing decision is made in Stage 2, and it is licensing if $\Theta = \theta_1$, and no licensing if $\Theta = \theta_2$.*

R5: *If $\pi_2 < \pi < \min\{\pi_1, \widehat{\pi}_o\}$, then the OEM does not license its technology and makes this decision in Stage 1.*

The above proposition is based on comparing the expected profits of the OEM. The licensing decision made in the first two bullets is not affected by the timing of this decision, that is, in Stage 1 or in Stage 2. Bullets 3 and 5 characterize the regions in the π-value space where the decision is made in Stage 1. Finally, bullet 4 gives the values of π where the licensing decision is made in Stage 2. Here, a low-realization of technology efficiency (θ_1) leads the OEM to license the technology, whereas high-realization value (θ_2) is a disincentive for licensing. The reason is that θ_2 generates high demand and profit, and therefore licensing may damage its demand and profit owing to competition. When facing the low-realization θ_1, the OEM prefers to license the technology to gain more external revenue.

As the ordering of the different values showing up in the proposition depends on the other parameter values, it is hard to clearly interpret the results. In the numerical subsection, we will provide a figure that will allow to visualize at a glance the result.

The next proposition characterizes the preferences of the two channel members in terms of licensing decision (licensing or not) and its timing (Stage 1 or Stage 2). This proposition, which is based on straightforward payoffs comparisons, is stated for completeness. The results are by no way easy to grab, and a visual representation is provided below. Still, one notes that in Cases 1 to 5 both players' interests are fully aligned, whereas in the remaining six cases, the preferences differ.

Proposition 5 *The channel members' preference on licensing strategy depends on external revenue margin as follows:*

Case 1 *If $\max\{\pi_2, \widetilde{\pi}_o\} < \pi < \pi_1$, then both players prefer licensing in Stage 1.*

Case 2 *If $\max\{\pi_2, \widehat{\pi}_o, \widehat{\pi}_c\} < \pi < \min\{\pi_1, \widetilde{\pi}_c\}$, then both players prefer licensing decision to be taken in Stage 2; licensing if $\Theta = \theta_1$, and no licensing if $\Theta = \theta_2$.*

Case 3 *If $\pi_2 < \pi < \min\{\pi_1, \widehat{\pi}_o, \widehat{\pi}_c\}$, then both players prefer a no licensing decision in Stage 1.*

Case 4 *If $\bar{\pi}_o < \pi < \pi_2$, or $\pi > \max\{\pi_1, \bar{\pi}_o, \bar{\pi}_c\}$, then both players prefer licensing, and there is no difference if this decision is made in Stage 1 or 2.*

Case 5 *If $\pi < \min\{\pi_2, \bar{\pi}_c\}$, or $\pi_1 < \pi < \min\{\bar{\pi}_o, \bar{\pi}_c\}$, then both players prefer no licensing, and there is no difference if this decision is made in Stage 1 or 2.*

Case 6 *If $\max\{\pi_2, \widehat{\pi}_o, \widetilde{\pi}_c\} < \pi < \min\{\pi_1, \widetilde{\pi}_o\}$, then the OEM makes the licensing decision in Stage 2, and chooses licensing if $\Theta = \theta_1$, and no licensing if $\Theta = \theta_2$, while the CM prefers licensing in Stage 1.*

Case 7 *If $\widehat{\pi}_o < \pi < \min\{\pi_1, \widehat{\pi}_c\}$, then the OEM makes the licensing decision in Stage 2, and it is licensing if $\Theta = \theta_1$, and no licensing if $\Theta = \theta_2$, while the CM prefers no licensing in Stage 1.*

Case 8 *If $\max\{\pi_2, \widetilde{\pi}_c\} < \pi < \widehat{\pi}_o$, then the OEM prefers no licensing in Stage 1, while the CM prefers licensing in Stage 1.*

Case 9 *If $\max\{\pi_2, \widehat{\pi}_c\} < \pi < \min\{\pi_1, \widehat{\pi}_o, \widetilde{\pi}_c\}$, then the OEM licenses the technology in Stage 1, while the CM prefers licensing decision in Stage 2, with licensing if $\Theta = \theta_1$, and no licensing if $\Theta = \theta_2$.*

Case 10 *If $\max\{\pi_1, \bar{\pi}_o\} < \pi < \bar{\pi}_c$, then the OEM prefers licensing, and there is no difference if this decision is made in Stage 1 or 2, while the CM prefers no licensing, and there is no difference if this decision is made in Stage 1 or 2.*

Case 11 *If $\max\{\pi_1, \bar{\pi}_c\} < \pi < \bar{\pi}_o$ or $\bar{\pi}_c < \pi < \min\{\pi_2, \bar{\pi}_o\}$, then the OEM prefers no licensing, and there is no difference if this decision is made in Stage 1 or 2, while the CM prefers licensing, and there is no difference if this decision is made in Stage 1 or 2.*

4.1 Numerical illustrations

Although all our results are analytical, we wish to provide in this section few numerical examples to give a visual illustration of (i) how some parameter values affect the licensing decision; and (ii) the shape of the different regions identified in Propositions 4 and 5. We recall that our model has the following 8 parameters:

$$\begin{aligned}
\text{Probability distribution parameters} &: \theta_1, \theta_2, \mu, \sigma^2, \alpha, \\
\text{Demand substitutability parameter} &: \delta, \\
\text{Licensing revenue sharing parameter} &: \tau, \\
\text{Royalty parameter} &: \pi.
\end{aligned}$$

We retain the following constellation of parameter values as a benchmark:

$$\theta_1 = 0.5, \theta_2 = 1, \delta = 0.5, \tau = 0.4, \alpha = 0.6, \pi = 0.3, \mu = 0.8, \sigma^2 = 0.06.$$

Figure 1 shows the impact of varying δ and τ on licensing option for different values for μ. (Note that varying μ while keeping unchanged the value of $\sigma^2 = 0.06$, requires that we adjust consequently the values of θ_1 and θ_2.) In Figure 1, the plane is divided by a solid curve into two regions, above which no licensing is the optimal choice and below which licensing is the best option. This reflects that it is beneficial to choose licensing when τ is high and δ is low. These results are intuitive as high revenue rate motivates the OEM to license the technology, while higher technology competition deters the OEM from doing so. In particular, the licensing region shrinks, and no-licensing region expands with the increase of mean μ. High mean value of technology effectiveness boosts the demand and increases profit, which dominates the external revenue from licensing.

Figure 2 exhibits the impact of varying δ and τ on licensing decision for different values of variance σ^2. Again, we need to adjust θ_1 and θ_2 when varying σ^2 while keeping $\mu = 0.8$. We see that a larger variance σ^2 expands the no-licensing region and shrinks the licensing region, meaning that larger volatility reduces the OEM's motivation to license the technology.

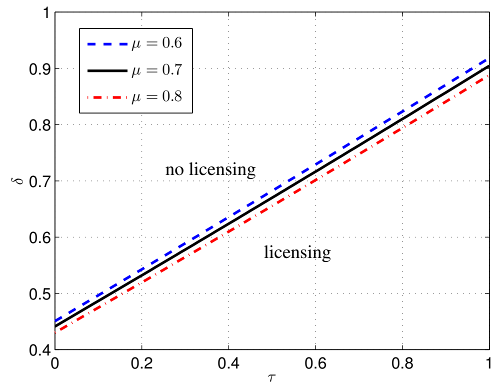

Figure 1: Licensing decision when mean μ varies

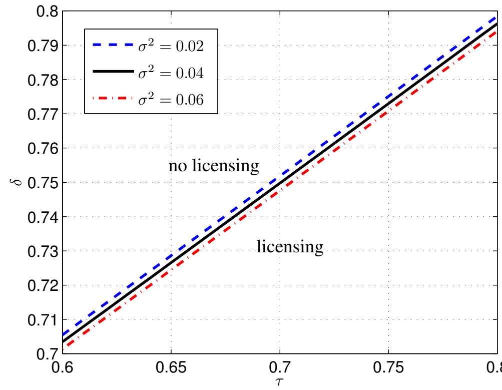

Figure 2: Licensing decision when variance σ^2 varies

The probability distribution parameters of the stochastic technology effectiveness, i.e., θ_1, θ_2 and α, only affect the equilibrium solution in Scenario 1 in terms of mean and variance, but have a significant influence on the results in Scenario 2, and in particular the licensing decision. To give an intuition about the effects of probability distribution parameters on optimal licensing strategy, we report two examples in Table 2 where in both cases the distribution's mean μ and variance σ^2 are kept at 0.8 and 0.06, respectively.

Table 2: Impact of probability distribution on licensing strategy

τ	π	θ_1	θ_2	α	μ	σ^2	Decision Stage	Licensing decision
Example 1								
0.62	0.216	0.5	1	0.6	0.8	0.06	2	Depend on realization
		0.31	0.92	0.8	0.8	0.06	1	Licensing
Example 2								
0.67	0.198	0.5	1	0.6	0.8	0.06	1	No licensing
		0.31	0.92	0.8	0.8	0.06	2	Depend on realization

Examples 1 and 2 show that when we modify the probability distribution, keeping all other parameters at their benchmark values, the timing of licensing decision changes. In Example 1, the shift is from Stage 2 to Stage 1 and is the other way around in Example 2. Further, in Example 1 the decision changes from depending on realization to licensing, whereas in Example 2, the change is from no licensing to depending on the realization of the stochastic process. In a nutshell, the clear-cut conclusion is that the probability distribution of stochastic technology effectiveness significantly affects, not only quantitatively but also, qualitatively the OEM's licensing strategy.

Figure 3 illustrates Proposition 4 that states that the OEM's licensing strategy depends on the relationship between π and $\pi_1, \pi_2, \bar{\pi}_o, \widetilde{\pi}_o, \hat{\pi}_o$. In this figure, we use the notation S1/2-L, S1/2-NL, S1-L, S2-D, S1-NL to represent the different cases, with the first entry representing the stage in which the licensing decision is made, that is, S1 for Stage 1, S2 for Stage 2 and S1/2 when the stage does not matter, and the second entry refers to the result, with NL referring to no licensing, L to licensing and D meaning that the decision depends on the realization of the stochastic process.

As seen from Figure 3, there exist two thresholds for π, namely, $\pi_h = 0.22$ and $\pi_l = 0.195$, and two thresholds for τ, i.e., $\tau_h = 0.705$ and $\tau_l = 0.598$. The main takeaways from this figure are: (i) Loosely speaking, if $\pi \leq \bar{\pi}_o$, then the optimal decision is no licensing and this seems to be fairly intuitive. Indeed, if the royalty is too low, then there is no point for the OEM to license its technology and expose itself by the same token to competition. (ii) If $\pi \geq \bar{\pi}_o$, then we have the mirror case where licensing is profitable. (iii) There is an in-between region (S2-D) where the decision depends on the realization of the stochastic process. As we can see, this region is relatively small. (iv) The value of $\bar{\pi}_o$ depends on the royalty π and the revenue sharing parameter τ. The higher the value of the royalty, the less share of revenue it takes to the OEM to license the technology. Finally, (v) we note that in most of the space, it does not matter if the licensing decision is made in Stage 1 or in Stage 2.

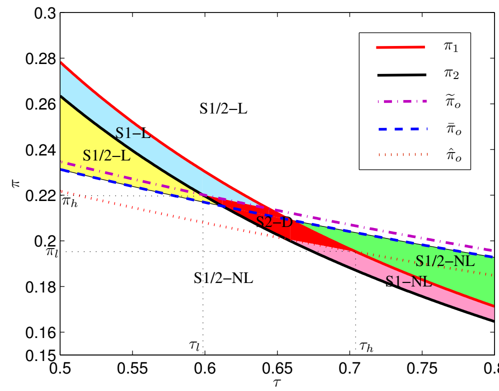

Figure 3: Different regions characterized in Proposition 4

Figure 4 illustrates the results stated in Proposition 5, with Case i referred to by Ci. Recall that in Cases 1 to 5, the two partners in the supply chain have their objectives aligned in terms of licensing decision. We see that these cases occupy a large part of the space, which is good news in terms of avoiding any possible conflicts. Note that for this parameter constellation, Case 8 does not materialize.

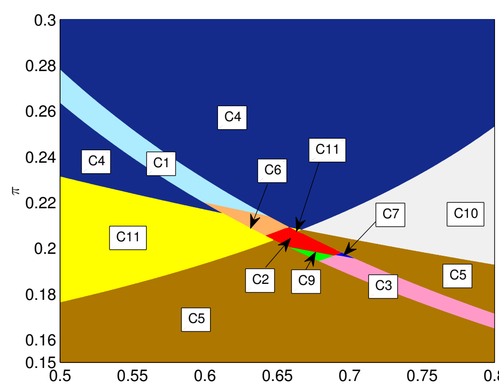

Figure 4: Different regions characterized in Proposition 5

5 Conclusion

In this paper, we considered a simple model of R&D cooperation in a supply chain. We characterized pricing, investment and cost-sharing equilibrium strategies in two scenarios, namely, a scenario where licensing decision can be taken before R&D and market uncertainties are resolved, and a scenario where this decision can be postponed to the sales stage where these uncertainties are resolved. Our focus was on the strategic licensing decision of the OEM. Our main results can be summarized as follows: 1) Uncertainty factor promotes technology investment, expected retail margin and profits for CM and OEM, but exerts an ambiguous effect on investment sharing rate. 2) If the licensing decision is made in Stage 1, then there exists a threshold on royalty, above which the OEM is willing to license the technology, below which it does not. 3) Larger uncertainty and competition spur the OEM to license the technology, but a low revenue sharing rate prevents it from doing it. 4) The OEM is more likely to license its technology and announce this option in the first stage when the royalty is high and the revenue sharing rate is low, while it prefers not to license in the first stage in the context of a relatively low external margin and a relatively high revenue sharing rate. Moreover, in the face of a moderate revenue margin and a moderate revenue sharing rate, the OEM will make the licensing decision in the second stage, and the option depends on the technology effectiveness realizations. 5) Different probability distribution of stochastic technology effectiveness may result in different licensing strategies.

As in any modeling effort, we made some simplifying assumptions for the sake of clarity. Some of these simplifications are rather technical and can be removed relatively easily, e.g., adopting a more general probability distribution than a two-point distribution. Others would change drastically the model but are worth considering. In particular, giving a strategic role to the licensee instead of modeling its presence only through an impact on OEM's demand is clearly of interest. Finally, the cost-sharing mechanism of R&D investments is modeled here as a parameter, and considering it as a strategic variable could provide some interesting insights.

Appendix

5.1 Proof of Proposition 1

By backward induction, we first solve the CM's second-stage problem:

$$\max_{w}\ \Pi_c = w(1-(m+w)+\theta x-\delta\Lambda\eta\theta x)+(1-\tau)\pi\Lambda\eta\theta x-(1-\phi)x^2. \tag{28}$$

Using the first-order condition, we get

$$w(\theta)=\frac{1}{2}\theta x(1-\delta\eta)+\frac{1}{2}(1-m). \tag{29}$$

Taking it account, we then solve the OEM's second-stage problem:

$$\max_{m}\ \Pi_o = m(1-(m+w)+\theta x-\delta\Lambda\eta\theta x)+\tau\pi\Lambda\eta\theta x-\phi x^2. \tag{30}$$

Similarly, the optimal retailer margin m is calculated as

$$m(\theta)=\frac{1}{2}\theta x(1-\delta\eta)+\frac{1}{2}. \tag{31}$$

With the second-stage response functions (29) and (31), the CM's first-stage problem is

$$\max_{x}\ E[\Pi_c]=E[w(\Theta)(1-(m(\Theta)+w(\Theta))+\Theta x-\delta\Lambda\eta\Theta x)+(1-\tau)\pi\Lambda\eta\Theta x-(1-\phi)x^2]. \tag{32}$$

The corresponding solution is easy obtained as

$$x=\frac{\mu(8\eta\pi(1-\tau)+1-\delta\eta)}{16(1-\phi)-\xi(1-\delta\eta)^2}. \tag{33}$$

Next, with the consideration of (29), (31) and (33), and given Λ, solving the following OEM's first-stage problem:

$$\max_{\phi}\ E[\Pi_o]=E[m(\Theta)D+\tau\pi\Lambda\eta\Theta x-\phi x^2], \tag{34}$$

yields

$$\phi=\frac{8\Lambda\eta\pi\big(\xi(5-7\tau)(1-\delta\Lambda\eta)^2-16(1-3\tau)\big)+(1-\delta\Lambda\eta)\big(\xi(1-\delta\Lambda\eta)^2+48\big)}{16\big(5(1-\delta\Lambda\eta)+8\Lambda\eta\pi(1+\tau)\big)}. \tag{35}$$

Substituting (35) into (29), (31) and (33) yields the equilibrium solutions as given in (9)–(12).

5.2 Details of derivatives in Table 1

The derivatives of equilibrium strategies and payoffs given in Table 1 are as follows:

$$\frac{\partial\phi}{\partial\pi} = \frac{2(1-\delta)(3\tau-2)(16-3\xi(1-\delta)^2)}{(8\pi(1+\tau)+5(1-\delta))^2},$$
$$\frac{\partial\phi}{\partial\tau} = \frac{2\pi(8\pi+3(1-\delta))(16-3\xi(1-\delta)^2)}{(5(1-\delta)+8\pi(1+\tau))^2} > 0,$$
$$\frac{\partial\phi}{\partial\mu} = \frac{\mu(1-\delta)^2(8\pi(5-7\tau)+1-\delta)}{16(5(1-\delta)+8\pi(1+\tau))},$$
$$\frac{\partial\phi}{\partial\sigma^2} = \frac{(1-\delta)^2(8\pi(5-7\tau)+1-\delta)}{16(5(1-\delta)+8\pi(1+\tau))},$$
$$\frac{\partial x}{\partial\pi} = \frac{4\mu(1+\tau)}{16-3\xi(1-\delta)^2} > 0,$$
$$\frac{\partial x}{\partial\tau} = \frac{4\mu\pi}{16-3\xi(1-\delta)^2} > 0,$$
$$\frac{\partial x}{\partial\mu} = \frac{(8\pi(1+\tau)+5(1-\delta))(16+3(\mu^2-\sigma^2)(1-\delta)^2)}{2(16-3\xi(1-\delta)^2)^2} > 0,$$
$$\frac{\partial x}{\partial\sigma^2} = \frac{3\mu(1-\delta)^2(8\pi(1+\tau)+5(1-\delta))}{2(16-3\xi(1-\delta)^2)^2} > 0,$$
$$\frac{\partial m}{\partial\pi} = \frac{2\mu\theta(1+\tau)(1-\delta)}{16-3\xi(1-\delta)^2} > 0,$$
$$\frac{\partial m}{\partial\tau} = \frac{2\mu\theta\pi(1-\delta)}{16-3\xi(1-\delta)^2} > 0,$$
$$\frac{\partial m}{\partial\mu} = \frac{\theta(1-\delta)(5(1-\delta)+8\pi(1+\tau))(16+3(\mu^2-\sigma^2)(1-\delta)^2)}{4(16-3\xi(1-\delta)^2)^2} > 0,$$
$$\frac{\partial m}{\partial\sigma^2} = \frac{3\mu\theta(1-\delta\eta)^3(5(1-\delta)+8\pi(1+\tau))}{4(16-3\xi(1-\delta)^2)^2} > 0,$$
$$\frac{\partial E[\Pi_o]}{\partial\pi} = \frac{\mu^2(1+\tau)(5(1-\delta)+8\pi(1+\tau))}{4(16-3\xi(1-\delta)^2)} > 0,$$
$$\frac{\partial E[\Pi_o]}{\partial\tau} = \frac{\mu^2\pi(5(1-\delta)+8\pi(1+\tau))}{4(16-3\xi(1-\delta)^2)} > 0,$$
$$\frac{\partial E[\Pi_o]}{\partial\mu} = \frac{\mu(5(1-\delta)+8\pi(1+\tau))^2(16-3\sigma^2(1-\delta)^2)}{32(16-3\xi(1-\delta)^2)^2} > 0,$$
$$\frac{\partial E[\Pi_o]}{\partial\sigma^2} = \frac{3\mu^2(1-\delta)^2(5(1-\delta)+8\pi(1+\tau))^2}{64(16-3\xi(1-\delta)^2)^2} > 0,$$
$$\frac{\partial E[\Pi_c]}{\partial\pi} = \frac{\mu^2(8\pi(1-\tau^2)+(3-2\tau)(1-\delta))}{2(16-3(1-\delta)^2)} > 0,$$
$$\frac{\partial E[\Pi_c]}{\partial\tau} = -\frac{\mu^2\pi(1-\delta+4\pi\tau)}{16-3(1-\delta)^2} < 0,$$
$$\frac{\partial E[\Pi_c]}{\partial\mu} = \frac{\mu(5(1-\delta)+8\pi(1+\tau))(8\pi(1-\tau)+(1-\delta))(16-3\sigma^2(1-\delta)^2)}{16(16-3\xi(1-\delta)^2)^2} > 0,$$
$$\frac{\partial E[\Pi_c]}{\partial\sigma^2} = \frac{3\mu^2(1-\delta)^2(5(1-\delta)+8\pi(1+\tau))(8\pi(1-\tau)+(1-\delta))}{32(16-3\xi(1-\delta)^2)^2} > 0,$$

5.3 Proof of Proposition 2

The derivatives of $\bar{\pi}_o$ with regard to $\mu, \sigma^2, \delta, \tau$ are

$$\frac{\partial \bar{\pi}_o}{\partial \mu} = \frac{30\delta\mu(2-\delta)}{\sqrt{(16-3\xi)(1+\tau)(16-3\xi)(16-3\xi(1-\delta)^2)}} > 0,$$
$$\frac{\partial \bar{\pi}_o}{\partial \sigma^2} = \frac{15\delta(2-\delta)}{\sqrt{(16-3\xi)(1+\tau)(16-3\xi)(16-3\xi(1-\delta\eta)^2)}} > 0,$$
$$\frac{\partial \bar{\pi}_o}{\partial \delta} = \frac{5\big(3\xi(1-\delta)+\sqrt{(16-3\xi)(16-3\xi(1-\delta)^2)}\big)}{8(1+\tau)\sqrt{(16-3\xi)(16-3\xi(1-\delta)^2)}} > 0,$$
$$\frac{\partial \bar{\pi}_o}{\partial \tau} = -\frac{5\sqrt{9\xi^2(1-\delta)^2-48\xi(\delta^2-2\delta+2)+256}-(16-3\xi)(1-\delta)}{8(16-3\xi)(1+\tau)^2} < 0.$$

5.4 Proof of Lemma 1

Given x and ϕ, the second-stage responses with and without technology licensing in stage 2 are

$$m = \begin{cases} \frac{1}{2}\theta x(1-\delta) + \frac{1}{2}, & \Lambda = 1, \\ \frac{1}{2}\theta x + \frac{1}{2}, & \Lambda = 0, \end{cases} \tag{36}$$
$$w = \begin{cases} \frac{1}{4}\theta x(1-\delta) + \frac{1}{4}, & \Lambda = 1, \\ \frac{1}{4}\theta x + \frac{1}{4}, & \Lambda = 0. \end{cases} \tag{37}$$

Substituting (36) and (37) into the OEM's profit yields

$$\Pi_{o_2} = \begin{cases} \big(\frac{1}{8}\theta^2(1-\delta)^2 - \phi\big)x^2 + \big(\frac{1}{4}\theta(1-\delta) + \tau\pi\theta\big)x + \frac{1}{8}, & \Lambda = 1, \\ \big(\frac{1}{8}\theta^2 - \phi\big)x^2 + \frac{1}{4}\theta x + \frac{1}{8}, & \Lambda = 0. \end{cases}$$

Comparing the profits with and without licensing, the OEM prefers to license the technology ($\Lambda^* = 1$) when $x < \bar{x}$, otherwise, no licensing ($\Lambda^* = 0$) is a better option for the OEM. The corresponding retail margin and wholesale price are obtained in (18) and (19).

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