Decision Structure and Performance of Networked Technology Supply Chains

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Supply chains in key growth industries increasingly commercialize a critical piece of technology invented by an upstream technology supplier. The focal technology is licensed to specialist design firms and designed into products, which are fabricated by dedicated large-scale manufacturers. We examine a technology supplier's licensing decision in such emerging multi-party networked supply chains in which a downstream design firm's capability may not be publicly known. We find that the supply chain and firm profits are critically affected by whether or not a license agreement between a technology supplier and a design firm is kept confidential from a manufacturer. Instead of licensing to two downstream firms, a technology supplier may also license to an integrated firm with both design and manufacturing capabilities, which forms a conventional vertical supply chain. We compare a networked supply chain with a vertical supply chain, and show that the network model can, under some conditions, outperform the integrated configuration and increase profits for all supply chain entities. In particular, a downstream firm can be better off decentralized, with design and manufacturing functions taken by different firms. Our research helps explain the emergence of such networked supply chains and offer insights on how to structure them to improve outcomes.

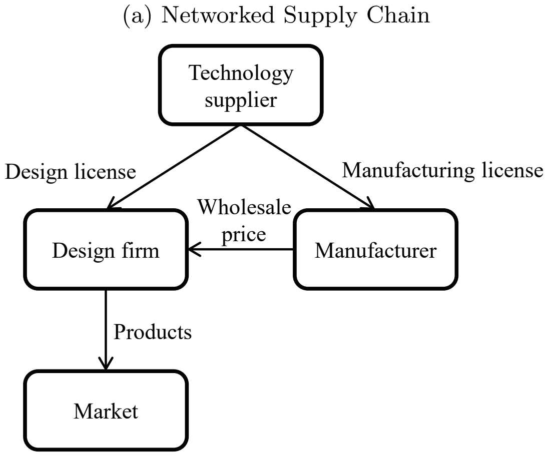
Key words: technology supply chain; networked supply chain; mechanism design; information asymmetry

1. Introduction

Innovative technology, commercialized in the form of intellectual property (IP), is powering a number of industries (e.g., electronics, semiconductors). In technology supply chains, a specialist upstream supplier, referred to as a technology supplier, invests in R&D to gain patents, copyrights, or other forms of IP. The technology IP is then licensed and embedded in products designed by a downstream company; these products are then launched and distributed to the market. In some cases, a downstream firm may be an integrated device manufacturer (IDM) that both designs and produces products, while in other cases a downstream design firm does not own manufacturing capacity and must collaborate with dedicated manufacturing partners to fabricate products. This latter case with trilateral interactions is particularly common in the electronics industry, as the increasing complexity of design, referred to as "micron madness," and the capital intensity of manufacturing lead to specialization and the emergence of fabless design firms (e.g., Marvel and NVIDIA) and large specialist chip manufacturing firms, or foundries (e.g., Taiwan Semiconductor Manufacturing Company). Some companies who were IDMs originally have even split into separate design firms and foundries. For example, AMD, a firm specializing in the design of computer processors, spun off its chip-manufacturing business into a separate company, GlobalFoundries (Kowaliski 2009). Also, Conexant, a firm providing products for voice and audio processing, divested its manufacturing arm into Jazz Semiconductor (EE Times 2002). The emergence and popularity of such networked supply chains is a bit surprising, for fragmentation usually generates economic friction and destroys value. For example, decentralization can result in double marginalization, which reduces total profits (Spengler 1973, Lariviere and Porteus 2001), or information asymmetry (Porteus and Whang 1991, Chu 1992) due to private information, which destroys profit. Then why do IDMs choose to spin off manufacturing capacities to become more decentralized? Our analysis offers one possible explanation for this trend that emerged in the electronic industry but may not be limited to it. What implications does this new supply chain structure have for the parties involved and the supply chain itself? This paper offers some managerial guidelines.

We refer to a supply chain with a three-party collaboration/trilateral interactions among the technology supplier, design firm, and manufacturer as a networked supply chain (NSC), whose structure is illustrated in Figure 1(a). In an NSC, an upstream technology supplier separately licenses its technology to design and manufacturing firms. The design firm purchases a *design license* from the technology supplier, designs its product based on the licensed IP, and relies on a manufacturer for production under a contractual agreement. In order to manufacture a product based on a technology supplier's IP, the manufacturer purchases a *manufacturing license* from the technology supplier. The complexity of manufacturing and concerns about yield and ramp-up time (Yoo 2008) motivate a manufacturer to license from the technology supplier well in advance to ensure that the long lead-time

Figure 1 Supply Chain Structures.



production process is optimized for the focal technology. Product design cycle times are usually shorter, so licensing to design firms happens later and closer to the product development and subsequent launch. The technology supplier's licensing decision to design and manufacturing firms in such a networked supply chain setting go beyond traditional quantity decisions, and have some unique features.

In such NSCs, coordination and incentive alignment among the technology, design, and manufacturing firms with trilateral interactions can be quite challenging. In addition, a downstream design firm usually has private information on its own design capability, to which the technology supplier is not privy. This information asymmetry issue complicates the problem even further. The extant literature has tackled licensing problems in integrated supply chains, whose structure is illustrated in Figure 1(b). However, to the best of our knowledge, the decision structure and performance of NSCs have not been explored in the existing literature. In this paper, we analyze the NSC model, and compare its performance with those under the traditional integrated supply chain model.

Because an NSC involves three entities, whether an agreement between two parties is observable to a third is an additional important issue absent in traditional integrated supply chains. Based on our field studies, detailed IP license terms tend to be highly confidential, and seem to be tailored to customers and industries. In the NSC model, managers often negotiate whether to keep license terms between two firms confidential to a third party, such as a manufacturer, and how to enforce such confidentiality. Accordingly, we consider two settings. In the first, the manufacturer observes the design license; in the second, the design license terms are kept confidential and unobservable to the manufacturer. We compare the technology supplier's optimal licensing strategy and each party's profit in the two settings with different information structures.

Using both interviews with Advanced RISC Machines (ARM) executives and information from trade magazines and the business press, we next present a case of a technology supply chain to highlight the underlying issues facing technology supply chains.

Technology Supply Chains: The Case of the Electronics Industry and ARM

One of the industries that embraced the technology licensing model over the last two decades is the semiconductor industry. In electronics design, an IP core, also called an IP block, is "a reusable unit of logic, cell, or chip layout design that is the intellectual property of one party".[1] A major technology supplier in the industry, Advanced RISC Machines (ARM), a U.K.-based company sells IP cores to its licensees who create subsystems, such as microcontrollers, CPUs, and systems-on-chips (SoCs), particularly suitable for portable devices. According to Thomson (2015), almost all smartphones around the world use ARM's technology. Every day, about 4.3 billion people, or 60 percent of the world's population, touch a device embedded with ARM's technology (Vance 2014).

Despite the prevalence of its technology, ARM does not produce or sell a single physical product. Instead, ARM creates a network or ecosystem of companies that share the underlying technology (Williamson and De Meyer 2012). ARM's customers include fabless semiconductor companies that are pure product design firms without manufacturing capabilities such as Marvel and Qualcomm, as well as IDMs with integrated design and manufacturing capabilities such as Texas Instruments or Samsung. These downstream licensees usually have better information about their own capabilities and the end market (Williamson and De Meyer 2012). This is particularly the case because the low entry barriers in the design space have caused substantial entries of new design firms. Many design firms are small with a relatively short history, whose true design capability is hard for others to observe. In addition, ARM, focusing on developing new technologies instead of selling in any particular product market, does not know the product market as well as its downstream licensees. Through its "Processor Foundry Program," ARM builds a three-way partnership among ARM itself, an approved foundry, and a fabless semiconductor firm,

[1] https://en.wikipedia.org/wiki/Semiconductor_intellectual_property_core

which enables fabless firms to efficiently use ARM's technology to design and manufacture SoCs (ARM 2016b). In the "Processor Foundry Program Product Schedule", ARM provides a list of approved foundries with process technologies that potential fabless customers can use for production (ARM 2016b). These foundries engage with ARM early and pay a license fee, called a technology access fee, to access ARM's technology roadmaps and latest releases. In other words, licensing to foundries happens earlier to accommodate the long lead-time in fine-tuning the manufacturing process, such that when product design commences, production issues are largely resolved, thereby encouraging fabless companies to embrace the foundry's technology. As one ARM executive stated it, "What good is a wafer (to a fabless customer) if it is not optimized for the core?" Design licenses with fabless firms usually combine a one-off licensing fee and a royalty for every unit of product that embodies the IP (Williamson and De Meyer 2012). Based on our interviews with ARM managers, design licenses may be customized based on the customer/industry situation that ARM faces. Technology-licensing discussions are currently confidential two-party discussions between ARM and the foundry on one hand, and between ARM and the fabless design firm on the other hand. Discussions with executives at ARM and other firms in the ecosystem underscore the sensitivity and confidentiality of licensing terms; executives do, at the same time, seem to question the benefits of such confidentiality.

Our analysis reveals that a technology supplier's optimal licensing strategy critically depends on the supply chain structure. In an NSC, the pooling strategy (i.e., offering one design license that both types of design firms will take) can be the technology supplier's optimal strategy under certain conditions, and it is also possible that the technology supplier may charge a positive royalty to the high-type design firm, which can be higher than the royalty charged to the low type. These features of the optimal licensing strategy are in sharp contrast with those in an integrated supply chain. In addition, we also find that the information structure has a significant impact on profits. A technology supplier can achieve a larger profit by keeping the design license terms confidential from the manufacturer. However, a design firm may have a different preference, and even the technology supplier itself may change its preference at different stages of the game. We show that an NSC with confidentiality, when compared to the benchmark integrated supply chain, can outperform the integrated configuration and yield gains for all supply chain entities. This is because that the technology supplier, in an NSC, is more likely to use a separating strategy (i.e., using different design licenses to target different types of design firms) and license the technology to a design firm regardless of its design capability. In contrast, in an integrated supply chain, the technology supplier is more likely to focus only on an IDM with high capability. Our results both explain the emergence of such NSCs and offer prescriptions for structuring them for superior outcomes. We also address when IDMs should consider spinning off their manufacturing operations to become pure design firms.

2. Literature Review

Our paper contributes to the literature of technology licensing, supply chain management with information asymmetry, and collaborative new product development.

Early work in technology licensing (e.g., Kamien and Tauman 1983, Kamien and Tauman 1986, Katz and Shapiro 1986, and Kamien et al. 1992) shows that in a symmetric information setting, fixed-fee licensing is better than per-unit royalty licensing if the licensor is not a competitor in the product market. However, the prevalence of contracts with output royalties has promoted great interest in explaining the rationale for using royalties. Many factors can contribute to the presence of output royalties in licensing contracts, including information asymmetry between the technology supplier and the licensee (e.g., Gallini and Wright 1990, Poddar and Sinha 2002, Sen 2005, Savva and Taneri 2015). Either the licensor or the licensee may have better information about the value of the innovation, production cost, or market demand (Poddar and Sinha 2002, Crama et al. 2008, Sen 2005). All these papers consider licensing strategies with respect to integrated licensees who have the capability to both design and produce products. In contrast, our model considers a design firm licensee without manufacturing capability, and hence a technology supplier faces a licensing problem with two downstream licensees, between whom there are price and quantity interactions. This three-party network structure involves more complex information flows and additional coordination issues absent in the traditional two-party integrated model.

In the new product development and innovation literature, researchers have examined how interactions between firms in a supply chain affect investment or innovation (Gupta and Loulou 1998, Gilbert and Cvsa 2003, Iyer et al. 2005, Bhaskaran and Krishnan 2009, Wang and Shin 2015). Ülkü and Schmidt (2011) show that the optimal supply chain structure and product architecture are inter-linked. Incorporating sellers' and buyers' demand-enhancing efforts, Agrawal and Oraiopoulos (2015) study contract structures between a seller and a buyer in which the contract terms also involve decision rights on who determines ex ante the menu of contracts and who decides ex post the pair of price and quantity. Crama et al. (2015) examine R&D collaboration between an innovator and a marketer, and investigate how control rights, options, payment terms, and timing allow an innovator to obtain maximum value from such collaboration. Considering information asymmetry, Xiao and Xu (2012) study strategic alliance between an innovator and a marketer with both exerting R&D efforts and with the marketer exerting marketing efforts. Specifically, they examine two types of royalty contracts depending on whether they are contingent on technical performance. The innovator's R&D capability is private information, and the marketer offers contracts to the innovator. They focus on separating contracts by excluding the pooling ones. In addition, Bhattacharya et al. (2014) compare milestone-based options contracts and buyout options contracts between research providers and clients in attaining the first-best outcome for the client that performs late-stage development activities. Using a model with information asymmetry, Savva and Taneri (2015) explain why equity-royalty contracts are used in university technology transfer, and show that such equity-royalty contracts are better than fixed-fee-royalty contracts due to fewer value destroying distortions. Except for Bhaskaran and Krishnan (2009), who study investment and innovation sharing between two horizontal firms, most of these papers–with or without information asymmetry–study vertical supply chains with one supplier and one buyer. In contrast, our paper considers a setting with a technology supplier licensing IP, instead of selling physical goods, to two downstream firms, who conduct design and manufacturing functions and interact based on a contractual agreement. A technology supplier's optimal strategy to orchestrate these two firms has not been studied before. In addition, a network structure's influence on a supply chain's profit is also an under-investigated question with important and practical implications. In this paper, we try to fill such gaps in the literature.

Extending a bilateral monopoly partnership to competitive settings, Erat and Kavadias (2006) and Erat et al. (2013) consider a two-tier supply chain with one technology provider and multiple downstream competing firms. They focus on a technology provider's technology introduction and pricing strategies. With respect to upstream competition, Adelman et al. (2016) consider two asymmetric competitive technology providers and multiple downstream firms. In their paper, the upstream firms decide the technological capability to offer to each downstream firm and the accompanying unit price, and the downstream firms choose their vendors and new quality levels. The paper demonstrates the impact of upstream competition on technology diffusion and identifies the situation when an under-investment problem can be solved. Although these papers involve more than two firms, they still consider a vertical supply chain structure, for firms in the same tier play similar roles. In contrast, the three entities we consider in our NSC model play different and complementary roles, thus forming a network structure instead of a vertical one.

In the literature studying high-tech industries, most existing research on the semiconductor industry (e.g., Erkoc and Wu 2005 and Wu et al. 2013) focuses on capacity expansion and coordination decisions, not IP issues. In contrast, our paper studies an emerging NSC model by focusing on IP licensing decisions. The coordination of decisions among multiple firms turns out to be an intricate question, as we discuss below.

3. Model

An upstream technology supplier develops and licenses technologies to a design firm and a manufacturer. The design license includes a one-time upfront licensing fee and a royalty fee for each unit of product sold. In practice, a technology supplier such as ARM may help design firms by providing starter kits (BBC 2015), reference designs, libraries (ARM 2016c), training courses (ARM 2016a), and even prototypes of products. In order to reflect such support from a technology supplier to design firms, we do not restrict the licensing fee to be nonnegative. We also analyze the case where the licensing fee must be nonnegative as an extension in Section 6.3, and show that our main insights remain the same. Consistent with the practice of ARM, we assume that the manufacturing license involves only a fixed upfront licensing fee. Because what affects the final selling quantity and firms' profits is the sum of royalties in the design license and the manufacturing license, incorporating a positive royalty fee in the manufacturing license does not change the technology supplier's optimal licensing strategy or each party's equilibrium profit. So the assumption of zero royalty in the manufacturing license is also without loss of generality.

The market potential of the product depends on the design firm's design competency using the new technology, which is its private information. We model this information asymmetry as simply and consistently with the prior literature as possible by assuming that the design firm's capability can be either high or low. The design firm with high (low) capability is referred to as high (low) type. The high-type design firm is able to develop a product of high demand with an inverse demand function $p = A_H - q$, whereas the low-type design firm can only capture low demand with an inverse demand function $p = A_L - q$ $(A_L < A_H)$. We define $\gamma = A_L/A_H$, which is the ratio of market potentials. The technology supplier does not know the design firm's capability but has a prior belief that the capability is high with probability β and low with probability $1 - \beta$, $0 < \beta < 1$.

The design firm and the manufacturer interact based on a wholesale price contract.[2] Without loss of generality, we normalize the manufacturer's unit production cost to zero, because having a positive per-unit product cost is effectively the same as reducing the demand intercepts. We also normalize the manufacturer's fixed cost to zero without loss of generality, because the technology supplier can simply reduce the manufacturing licensing fee to cover the manufacturer's fixed cost. When deciding the wholesale price to charge the design firm, the manufacturer has already observed the designed product. Based on the product's technical details and functionality, the manufacturer can infer whether the demand is high or low. However, at that time, the manufacturer may or may not be privy to the design license agreement between the technology supplier and the design firm. That is, the design license is a different piece of information from the design firm's type. In the NSC model, whether the manufacturer can observe the design license is an important element that affects the optimal wholesale price decision and the equilibrium results. Therefore, we study and compare two NSC models, one with the design license observable to the manufacturer in Section 4.1 and the other with the design license confidential in Section 4.2. The timeline for both settings is as follows:

(1) The technology supplier licenses to the manufacturer by proposing a one-time upfront licensing fee F_M to the manufacturer, who accepts this license as long as its expected profit is nonnegative. Alternatively, the technology supplier can specify that the manufacturing licensing fee will be refunded if no sales materialize. By setting a non-refundable licensing fee the same as the expected payment from the manufacturer

[2] In practice, due to the limited number of manufacturers with cutting-edge manufacturing technologies and expensive capital investment, a manufacturer's bargaining power is usually high when compared to that of a design firm. Thus, we consider the case with the wholesale price offered by the manufacturer. Nevertheless, we conducted the analysis when the wholesale price is determined via non-cooperative bargaining between the design firm and the manufacturer, and find that the technology supplier's optimal licensing strategy and all the firms' profits are continuous in the manufacturer's bargaining power. As long as the manufacturer's bargaining power is high enough, all our qualitative results still hold.

in the refundable case, the two alternatives are mathematically equivalent. Thus, we assume that licensing fee is non-refundable in the analysis for exposition simplicity.[3]

(2) The technology supplier licenses IP to the design firm with private type information. Denote r_i and F_i, $i \in \{L, H\}$ as the per unit royalty and one-time licensing fee for type i design firm. The technology supplier can either offer one license (r_H, F_H) to attract the high-type design firm only (high-type-only strategy), or propose a menu of two licenses–(r_L, F_L) targeting the low type and (r_H, F_H) targeting the high type–to attract both types (inclusive strategy).

(3) The design firm, per its type, decides whether to accept the license and, if facing two choices, which license to take. The design firm then designs the product, and the market potential is realized.

(4) Observing the design firm's end product and type, the manufacturer decides the wholesale price w_i, $i \in \{L, H\}$. The design license terms between the technology supplier and the design firm are observable to the manufacturer in the observable NSC model, and unobservable in the confidential NSC model.

(5) The design firm determines the order quantity q from the manufacturer and sells end products at the market-clearing price $p = A_i - q$, $i \in L, H$.

The notation is summarized in Table 1. We now derive the equilibrium outcomes.

4. Analysis

Our analysis of the NSC depends on whether the design license is observable to the manufacturer.

4.1. NSC Model with Observable Design License

In this subsection, we derive the technology supplier's optimal licensing strategy and firms' equilibrium profits in an NSC when the design license is observable to the manufacturer. We start by considering the design firm's and manufacturer's respective problems.

[3] In practice, refundable payments can avoid the situation in which the manufacturer has paid the licensing fee upfront, but ex post there is no business from the technology supplier (e.g., the technology supplier's strategy is to attract the high-type design firm only, but the design firm turns out to be low type). However, for the sake of simplicity, we use non-refundable manufacturing licensing fee due to its mathematical equivalence to the refundable payments.

Table 1 Summary of the notation

Symbol	Description
β	Technology supplier's prior probability that the design firm has high capability.
A	Intercept in the inverse demand function.
γ	The ratio of market potentials, i.e., A_L/A_H.
q	Selling quantity of end products.
w	Wholesale price.
x	Effective demand, i.e., $A-w$.
r	Royalty charged to the design firm (or IDM).
F_i	Licensing fee charged to type i design firm (or IDM).
F_M	Licensing fee in the manufacturing license.
π	Profit.
Π_T	The technology supplier's profit excluding F_M, i.e., $\pi_T - F_M$.
Subscript	
T	Technology supplier.
$i \in \{L, H\}$	Type-i design firm (or IDM).
M	Manufacturing firm.
SC	Whole supply chain.
First superscript	
O	NSC model with observable design license.
C	NSC model with confidential design license.
I	Integrated supply chain model.
Second superscript	
I	Inclusive licensing strategy.
S	(Interior) separating licensing strategy.
B	Boundary high-royalty separating licensing strategy.
P	Pooling licensing strategy.
H	High-type-only licensing strategy.

The subscript, first superscript, and second superscript (if used) denote the player, supply chain model, and technology supplier's licensing strategy, respectively. For example, π_T^{OP} represents the technology supplier's profit when using the pooling licensing strategy in an NSC with observable design license.

4.1.1. Design and Manufacturing Firms' Decisions If a type i $(i = H, L)$ design firm takes a license (r, F) $(r \leq A_i)$ from the technology supplier and a wholesale price w $(w \leq A_i - r)$ from the manufacturer, then its profit maximization problem is

$$\max_{q} \ (A_i - q - w - r)\, q - F, \tag{1}$$

where q denotes the design firm's selling quantity. Solving this problem gives the design firm's optimal quantity $(A_i - r - w)/2$. Note that if $w > A_i - r$, then the design firm will choose not to sell the product. When setting the wholesale price, the manufacturer knows the design firm's type. Anticipating the design firm's optimal quantity decision, the manufacturer's profit maximization problem over w_i is $\max_{w_i \leq A_i - r}(A_i - r - w_i)w_i/2 - F_M$. Solving this problem, we obtain the manufacturer's optimal wholesale price $w_i(r) = (A_i - r)/2$. To ensure $w_i(r) \leq A_i - r$, $r \leq A_i$ must hold. Otherwise, the design firm will not set a positive selling quantity. Substituting $w_i(r) = (A_i - r)/2$ back into the design firm's optimal quantity, we derive selling quantity q_i^O as a function of the royalty r as $q_i^O(r) = (A_i - r)/4$, and the corresponding optimal profit for the design firm and the manufacturer are:

$$\pi_i^O(r,F) = \frac{(A_i - r)^2}{16} - F, \tag{2}$$

$$\pi_M^O(r,F_M,A_i) = \frac{(A_i - r)^2}{8} - F_M. \tag{3}$$

If $r > A_i$, the design firm cannot profitably sell the product. Therefore, the type i design firm will accept a license (r,F) only if $r \le A_i$ and $\pi_i^O(r,F) \ge 0$.

4.1.2. Technology Supplier's Problem When designing the manufacturing license, neither the technology supplier nor the manufacturer has information about the demand. Thus, the manufacturer chooses to participate as long as its expected profit is nonnegative, and it is optimal for the technology supplier to set the one-time licensing fee F_M to extract all the expected profit from the manufacturer.

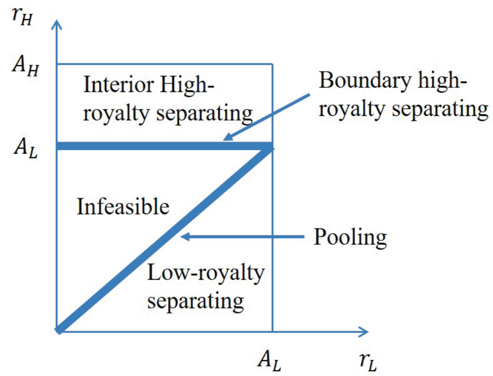
When proposing the design license, the technology supplier needs to choose between the high-type-only strategy and the inclusive strategy. We first derive its optimal license terms and profit under the inclusive strategy, and then compare this profit with that in the high-type-only strategy to pin down its final optimal licensing strategy.

Inclusive strategy

By the revelation principle (Myerson 1979), it is sufficient to consider the truth-telling mechanism. The technology supplier offers two design licenses: (r_H, F_H) targeting the high-type design firm and (r_L, F_L) targeting the low type. Either type must collect a nonnegative profit by taking the license that is intended for it. The individual rationality constraint for type i (IRi) is: $\pi_i^O(r_i, F_i) \ge 0$ and $r_i \le A_i$, $i \in \{L, H\}$. In addition, the design firm must prefer to truthfully reveal its own type and take the license that targets it rather than pretend to be the other type. If a type i design firm reports to be type $j, j \ne i$ and $r_j < A_i$, its profit is $\pi_i^O(r_j, L_j)$. If $r_j \ge A_i$, then the type i design firm obtains zero profit by reporting to be type j and thus has no incentive to do so. Therefore, the incentive compatibility constraint for type i (ICi) is: $\pi_i^O(r_i, F_i) \ge \pi_i^O(r_j, L_j)$ or $r_j \ge A_i$, $i \in \{L, H\}$ and $i \ne j$. Note that by the IRL constraint, $r_L \le A_L$ must hold. Therefore, $r_L \ge A_H$ cannot hold by $A_H > A_L$, and the ICH constraint must require $\pi_H^O(r_H, F_H) \ge \pi_H^O(r_L, F_L)$. To summarize, the technology supplier's problem is to maximize its expected profit subject to IRCs and ICCs, i.e.,

$$\max_{\{(r_H,F_H),(r_L,F_L)\}} \beta r_H q_H^O(r_H) + (1-\beta)\, r_L q_L^O(r_L) + \beta F_H + (1-\beta)\, F_L \tag{4a}$$

Figure 2 **Technology Supplier's Inclusive Strategy in the NSC Model with Observable Design License**



$$\text{s.t. IRH: } \pi_H^O(r_H, F_H) \geq 0 \text{ and } r_H \leq A_H, \tag{4b}$$

$$\text{IRL: } \pi_L^O(r_L, F_L) \geq 0 \text{ and } r_L \leq A_L, \tag{4c}$$

$$\text{ICH: } \pi_H^O(r_H, F_H) \geq \pi_H^O(r_L, F_L), \tag{4d}$$

$$\text{ICL: } \pi_L^O(r_L, F_L) \geq \pi_L^O(r_H, F_H) \text{ or } r_H \geq A_L. \tag{4e}$$

In the inclusive strategy, the technology supplier should set the licensing fee F_L to extract all profits from the low type, and F_H so that the high type is indifferent between taking its own license and accepting the low-type license. The technology supplier's mechanism design problem is simplified as follows:

LEMMA 1. *In the NSC model with observable design license, the technology supplier's optimal royalties when using the inclusive licensing strategy can be obtained by solving:*

$$\max_{\{r_H \leq A_H, r_L \leq A_L\}} \Pi^{OI}(r_H, r_L) \tag{5a}$$

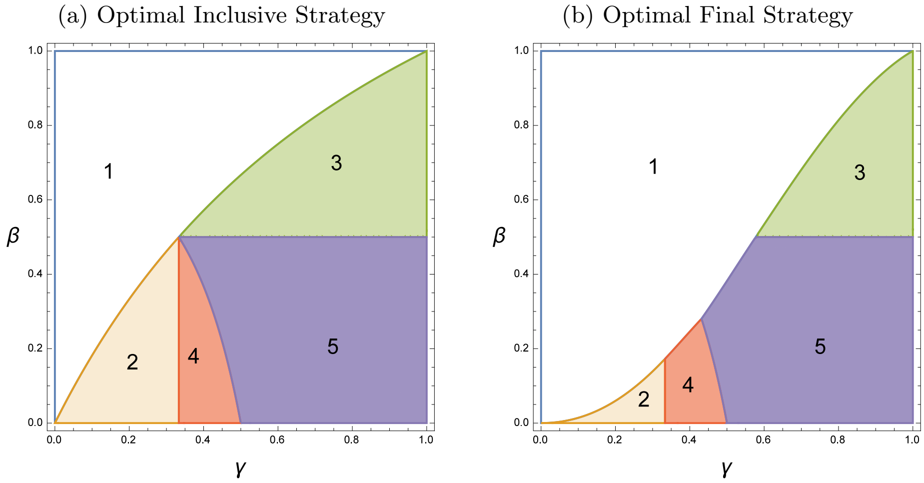
$$s.t.\ r_H \leq r_L \ or\ r_H \geq A_L, \tag{5b}$$

where

$$\begin{aligned}\Pi^{OI}(r_H, r_L) =& \beta q_H^O(r_H) r_H + (1-\beta)\, q_L^O(r_L) r_L + \beta \frac{(A_H - r_H)^2}{16} \\ &+ \frac{(A_L - r_L)^2}{16} - \beta \frac{(A_H - r_L)^2}{16}.\end{aligned} \tag{6}$$

The technology supplier's inclusive strategy can be a pooling strategy or a separating strategy. The high-type design firm has a higher demand than the low type, and thus can take better advantage of a low royalty. Meanwhile, the high-type design firm is able to afford a higher royalty. As a result, there are two ways that the technology supplier can

Figure 3 The Technology Supplier's Optimal Strategy in the NSC Model with Observable Design License



Note. 1.High type only; 2.Interior high-royalty separating; 3.Interior low-royalty separating; 4.Boundary high-royalty separating; 5.Pooling.

prevent the low type from taking the high type's license: either charging the high type a low royalty combined with a high licensing fee (i.e., low-royalty separating), or charging a high royalty that the low type cannot afford (i.e., high-royalty separating). In the high-royalty separating strategy, the high royalty can be strictly higher than A_L (interior high-royalty separating strategy) or exactly the same as A_L (boundary high-royalty separating strategy). The feasible regions and the corresponding strategies are illustrated in Figure 2.

Solving the constrained optimization problem, we derive the technology supplier's optimal inclusive strategy, as illustrated in Figure 3(a).[4]

Technology supplier's final optimal strategy

The technology supplier may also use the high-type-only strategy, in which case its problem is to maximize profit from the high type subject to the high-type design firm's participation constraint, i.e.,

$$\max_{\{r_H, F_H\}} \beta \left(q_H^O(r_H) r_H + F_H\right)$$
$$\text{s.t. } \pi_H^O(r_H, F_H) \geq 0 \text{ and } r_H \leq A_H.$$

Solving for the optimal high-type-only strategy, and comparing the technology supplier's optimal profit by using the high-type-only strategy with that obtained by using the inclusive strategy, we have the following results.

[4] The detailed mathematical expressions are relegated to the appendix.

Proposition 1. *There exists an increasing function $\hat{\gamma}(\beta)$, such that in the NSC model with observable design license, the technology supplier's optimal licensing strategy is shown below*

$\gamma \leq \hat{\gamma}(\beta)$	*high type only*
$\gamma > \hat{\gamma}(\beta)$ *and* $\beta > 1/2$	*interior low-royalty separating*
$\gamma > \hat{\gamma}(\beta)$ *and* $\beta \leq 1/2$	*changes from interior high-royalty separating, to boundary high-royalty separating, and finally pooling as* γ *increases from* 0 *to* 1.

The optimal royalties and licensing fees are:

- $r_H^{OH} = \frac{A_H}{3}$, $F_H^{OH} = \frac{A_H^2}{36}$ *in the high-type-only strategy;*
- $r_L^{OS} = \frac{(1-2\beta)A_L+\beta A_H}{3(1-\beta)}$, $F_L^{OS} = \frac{(\beta A_H-(2-\beta)A_L)^2}{144(1-\beta)^2}$ *and* $r_H^{OS} = \frac{A_H}{3}$, $F_H^{OS} = \frac{(11\beta-5)A_H^2+3(1+\beta)A_L^2+6(1-3\beta)A_H A_L}{144(1-\beta)}$ *in both interior high-royalty and low-royalty separating strategies;*
- $r_H^{OB} = A_L$, $F_H^{OB} = \frac{(A_H-A_L)(\beta A_H-(2-\beta)A_L)}{24(1-\beta)}$ *and* $r_L^{OB} = r_L^{OS}$, $F_L^{OB} = F_L^{OS}$ *in the boundary high-royalty separating strategy;*
- $r_H^{OP} = r_L^{OP} = \frac{A_L+2\beta(A_H-A_L)}{3}$, $F_H^{OP} = F_L^{OP} = \frac{((1+\beta)A_L-\beta A_H)^2}{36}$ *in the pooling strategy.*

Proposition 1 is illustrated in Figure 3(b). The technology supplier's optimal licensing strategy is contingent on two factors: the technology supplier's prior belief that the design firm has high capability, β, and the ratio of market potentials γ. When γ is low, i.e., $\gamma \leq \hat{\gamma}(\beta)$ (area 1), the high demand is much larger than the low demand, so the revenue from the high type is more important. Thus, the technology supplier uses the high-type-only strategy to extract as much profit as possible from the high type. The threshold $\hat{\gamma}(\beta)$ is increasing in β. As β increases, the probability of high-type design firm increases, so the technology supplier is more likely to focus only on the high-type and use the high-type-only strategy. When $\gamma > \hat{\gamma}(\beta)$, both types are important revenue sources for the technology supplier, and the inclusive strategy should be adopted.

The optimal licensing strategy in the NSC presents several unique features compared with that in traditional purely vertical supply chains derived in the literature. First, in the vertical supply chain with two parties, the upstream technology supplier's optimal inclusive strategy is always separating (Sen 2005, Antelo 2012, Poddar et al. 2002). But in our NSC model, there are more possibilities. Pooling can also be the optimal strategy, and this occurs when the two types are very similar (i.e., large γ, in area 5 of Figure 3(b)).

Second, in a vertical supply chain, the license for the high type must be a pure fixed fee license, or $r_H = 0$. However, in the NSC model, r_H is positive for all licenses. This is because in the NSC model, the manufacturer charges a positive wholesale price and creates inefficiency; setting a zero royalty leaves room for the manufacturer to collect more profit. As a counteractive action, the technology supplier optimally sets a positive r_H. The optimal positive r_H is also due to the technology supplier's lack of commitment power. If the technology supplier could commit to a zero royalty when it signs with the manufacturer, then the supplier can charge higher licensing fees for both the manufacturing license and design license. However, since the technology supplier cannot commit to a zero royalty upfront, it cannot extract the additional profit from the manufacturer using the licensing fee in the manufacturing license. In such a case, ex post, the technology supplier is better off charging a positive royalty and collecting profits from both the royalty and licensing fees. We will discuss further about the roles of commitment and information in Section 4.3.

Third, the technology supplier always sets $r_L > r_H = 0$ to separate the high and low types in a vertical supply chain. Whereas the possibility of $r_H > r_L$ under the separating strategy in the NSC model presents a sharp contrast. If γ is small (area 2), the market potential difference is high, and the two types can be easily separated due to their significant difference. Then the technology supplier optimally charges a higher royalty to the high-type design firm to achieve separation, and the optimal strategy is interior high-royalty separating. As γ increases (area 4), the market potential difference becomes smaller. The technology supplier's optimal strategy is to set $r_H = A_L > r_L$ (boundary high-royalty separating strategy) in order to prevent the low type from taking the high-type license.

4.2. NSC Model with Confidential Design License

In the previous subsection, we assume that the manufacturer, when it determines the wholesale prices, can observe the design license. However, this may not always be the case, as the technology supplier and the design firm may choose to keep the design license confidential. If the design license is confidential, after the manufacturer takes the manufacturing license, then the technology supplier decides the design license, and the manufacturer decides the wholesale price based on rational expectations of the other party's decision. They also take into consideration the design firm's optimal reaction to the wholesale price and design license. In our proceeding analysis, we focus on pure strategy equilibria.

Manufacturer's best response

If a type i design firm takes a license with a licensing fee F and a royalty r, given a wholesale price w, then its profit maximization problem is the same as that in equation (1), and the optimal selling quantity is $(A_i - r - w)/2$. The manufacturer makes its wholesale price decision based on its rational expectation of the royalty. Denote the manufacturer's belief of the royalty in the design license as $\tilde{r}$. Anticipating the design firm's optimal decision, the manufacturer's profit maximization problem is

$$\max_{w_i \le A_i - \tilde{r}} w_i \frac{A_i - \tilde{r} - w_i}{2} - F_M. \tag{7}$$

Solving this problem, we obtain the manufacturer's optimal wholesale price as a function of its belief of the royalty $\tilde{r}$:

$$w_i^C(\tilde{r}) = \frac{A_i - \tilde{r}}{2}. \tag{8}$$

Technology supplier's best response

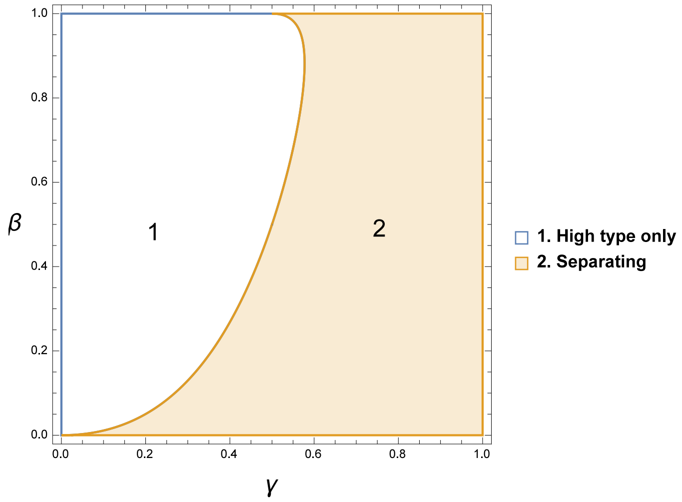
Because the manufacturer does not observe the actual design license, its wholesale price decision depends on its belief of the royalty $\tilde{r}$ instead of the actual royalty r in the design license. Thus, the impact of a wholesale price on the design firm is the same as reducing the intercept of the inverse demand function. We denote the design firm's effective demand as x_i, $x_i = A_i - w_i$. Then taking the manufacturer's wholesale prices w_H, w_L as given, the technology supplier is effectively facing two types of design firms with inverse demand functions $p = x_i - q$, $i \in \{L, H\}$. If the type i design firm takes a license (r, F) $(r \le x_i)$, then its profit maximization problem is $\max_q (x_i - q - r)\, q - F$. Solving this problem gives us the optimal quantity $q_i^C(r) = (x_i - r)/2$, and its corresponding design firm's profit $\pi_i^C(r, F) = (x_i - r)^2/4 - F$. Note that if $r > x_i$, then the design firm cannot profitably sell the product. Therefore, the type i design firm earns a nonnegative profit by taking a license (r, F) only if $r \le x_i$ and $\pi_i^C(r, F) \ge 0$.

In any pure strategy equilibrium, depending on the relationship between x_H and x_L, there are three possibilities: $x_H < x_L$, $x_H = x_L$, and $x_H > x_L$. We first solve the technology supplier's optimal response when $x_H > x_L$ and present the results in the following lemma:

LEMMA 2. *Denote* $\bar{\gamma}(\beta) = \frac{\beta^2 + (1-\beta)\sqrt{\beta(1-\beta)}}{1 - \beta + \beta^2}$. *In the NSC model with confidential design license, when* $x_H > x_L$,

- *if* $\frac{x_L}{x_H} \in [\bar{\gamma}(\beta), 1)$, *then the technology supplier's optimal licensing strategy is separating, and the royalties are* $r_H(x_L, x_H) = 0$ *and* $r_L(x_L, x_H) = \frac{\beta(x_H - x_L)}{1-\beta}$ *;*
- *if* $\frac{x_L}{x_H} \in (0, \bar{\gamma}(\beta))$, *then the technology supplier's optimal licensing strategy is high-type-only, and the royalty is* $r_H(x_H) = 0$.

Figure 4 **The Technology Supplier's Optimal Strategy in the NSC Model with Confidential Design License**



We next discuss the other two cases. If $x_H < x_L$, then the low-type design firm has a higher effective demand than the high type. In this case, the technology supplier's mechanism design problem is similar after we switch the effective demand parameters x_L, x_H, and replace β with $1-\beta$. In other words, the technology supplier is facing a design firm whose demand is high (i.e., $p = x_L - q$) with probability $1-\beta$ or low (i.e., $p = x_H - q$) with probability β. If $x_H = x_L$, then from the technology supplier's point of view, the two types are effectively the same and it is optimal to set a zero royalty and extract all profits using the licensing fee.

The equilibrium

Given both the technology supplier's and the manufacturer's best responses, we can now solve for the equilibrium, which is presented in the following proposition.

Proposition 2. *In the NSC model with confidential design license, $x_H > x_L$ always holds. Define $\underline{\gamma}(\beta) = \frac{\beta(2\beta-1)+(2-\beta)\sqrt{(1-\beta)\beta}}{2(1-\beta+\beta^2)}$. Then $\underline{\gamma}(\beta) < \bar{\gamma}(\beta)$ and we have:*

- *If $\gamma < \underline{\gamma}(\beta)$, then in equilibrium, the technology supplier uses the high-type-only strategy. The equilibrium decisions are $r_H^{CH} = 0$, $F_H^{CH} = A_H^2/16$, and $w_H^{CH} = A_H/2$.*
- *If $\gamma \geq \underline{\gamma}(\beta)$, then in equilibrium, the technology supplier uses the separating strategy. The equilibrium decisions are $r_H^{CS} = 0$, $F_H^{CS} = ((8-7\beta)\beta A_H^2 - 12(1-\beta)\beta A_H A_L + 4(1-\beta^2)A_L^2)/(8-4\beta)^2$, $r_L^{CS} = \beta(A_H - A_L)/(2-\beta)$, $F_L^{CS} = (\beta A_H - 2A_L)^2/(8-4\beta)^2$, $w_H^{CS} = A_H/2$, and $w_L^{CS} = (2A_L - \beta A_H)/(4-2\beta)$.*

Proposition 2 is illustrated in Figure 4. When γ is small (i.e., $\gamma \leq \underline{\gamma}(\beta)$), the market potential difference is large. Therefore, the technology supplier uses a high-type-only strategy to extract as much profit as possible from the high-type design firm. When γ is large (i.e., $\gamma \geq \underline{\gamma}(\beta)$), the market potential difference is small, and both types of design firms are important profit sources for the technology supplier. Thus, the technology supplier uses a separating strategy.

In addition, Proposition 2 shows that when the design license is confidential, the royalty that the technology supplier charges to the high-type design firm, r_H, is always zero. Recall that when the design license is observable to the manufacturer, r_H is always greater than zero, which creates supply chain inefficiency. When the design license is observable, the manufacturer's wholesale price depends on royalty in the design license. Therefore, by charging a positive r_H, the technology supplier can induce the manufacturer to offer a lower wholesale price. In contrast, if the design license is confidential, the technology supplier cannot affect the manufacturer's wholesale price, and thus sets r_H to zero in order to minimize the value-destroying distortion. This difference also highlights the benefit of confidentiality of the design license, as we discuss below.

4.3. Information Disclosure Strategies in a Technology Supply Chain

We now compare the two NSC models to analyze how the information transparency of the design license affects each party's profit, and how the technology supplier and design firm should manage the confidentiality of the design license. We first study the technology supplier's expected profit in an NSC.

Proposition 3. *In an NSC, the technology supplier's total profit is higher if the design license is kept confidential.*

As the technology supplier extracts all expected profit from the manufacturer, its total profit equals the total supply chain profit minus the information rent paid to the high-type design firm (if any). Therefore, the technology supplier's total profit is more closely related to the total supply chain profit, which depends on how efficiently the supply chain is operating. The summation of wholesale price and royalty affects supply chain efficiency, and increases in the royalty in both models. The royalty for the high type when the design license is observable to the manufacturer is positive, which is larger than the high-type royalty, zero, when the design license is confidential. Thus, when demand is high, keeping the design license confidential is more efficient. The royalty charged to the low type, however, may be higher or lower. Overall, the technology supplier benefits from keeping the design license confidential.

Even though the technology supplier obtains a higher total profit in an NSC with confidential design license, doing so is not easy. The technology supplier's willingness to reveal the design license may change over time. In an NSC, after the manufacturer takes the manufacturing license, the technology supplier always prefers to reveal the design license to the manufacturer, which reduces the manufacturer's ex-post profit (i.e., its earnings from the design firm). The design firm may or may not want to keep the design license confidential. In the observable model, the manufacturer's optimal wholesale price is decreasing in the technology supplier's royalty. In this case, the technology supplier has an incentive to raise royalties to push the manufacturer to lower wholesale prices. In contrast, if the design license is confidential, then the technology supplier cannot influence the manufacturer's wholesale price through its design license terms. As a result, revealing the design license to the manufacturer enables the technology supplier to affect the manufacturer's wholesale prices, which benefits the technology supplier but hurts the manufacturer.

Recall that Proposition 3 shows the technology supplier's total profit (i.e., its profit including the manufacturing licensing fee F_M) is larger when it keeps the design license confidential. F_M is used to extract all ex-post profit from the manufacturer. If the manufacturer believes that the design license will be kept confidential, then its ex-post profit is higher and, thus, it will accept a higher F_M. For the technology supplier, keeping the design license confidential allows it to charge a larger F_M but earn a smaller ex-post profit, and the former dominates the latter. As a result, its total profit including F_M is higher if the design license is confidential. Then how can the technology supplier convince the manufacturer to pay a higher licensing fee and achieve the benefit of keeping the design license confidential? The following proposition presents one mechanism to ensure confidentiality.[5]

PROPOSITION 4. *Suppose the technology supplier has the power to impose a confidentiality term in the design license, then if the technology supplier's contract with manufacturer contains a clause stating that the design licenses will not be revealed (either by itself or the design firm) to the manufacturer, with a breach penalty no smaller than* $\Pi_T^O - \Pi_T^C$

[5] In practice, confidentiality can also be credibly achieved due to reputation effect in repeated interactions or because the technology supplier licenses to multiple design firms.

paid by the technology supplier to the manufacturer, equilibrium outcomes in the NSC with confidential design license can be obtained.

In order to achieve the benefit of keeping the design license confidential and convince the manufacturer to pay a higher licensing fee, the technology supplier needs to credibly convince the manufacturer that the design licenses will not be revealed to the manufacturer. Because the penalty on the technology supplier for breaking such commitment is no smaller than $\Pi_T^O - \Pi_T^C$, which is the maximum gain that the technology supplier can get by deviating, the technology supplier does not benefit from ex post deviating and therefore always prefer to keep the design license confidential. The technology supplier is also able to prevent leakage from the design firm. In the next stage, when the technology supplier licenses to design firms, it has the incentive to set a confidentiality term in the design license together with a penalty on the design firm for breaking the confidentiality term. The technology supplier, being the sole supplier of certain intellectual properties, usually has a strong bargaining power to insist such a confidentiality clause in the design license. Finally, monitoring deviation is easy. The motivation of revealing the design license to the manufacturer (by either the technology supplier or the design firm) is to affect the manufacturer's wholesale price decision. Without convincing evidence, the manufacturer will not believe a revealed design license, and thus will not adjust its wholesale price decision based on any cheap talk. Therefore, the technology supplier (or the design firm) benefits from revealing only if it can *credibly* show the manufacturer what the actual design license is, in which case the manufacturer will have evidence to prove that the commitment has been broken and thus can impose the penalty.

Even though such a commitment imposes restrictions, the technology supplier still prefers it and has the incentive to make and honor such a commitment, because it enables the technology supplier to ensure confidentiality and get a larger profit.

5. Comparing NSC Models with the Benchmark Integrated Model

5.1. The Integrated Model

In contrast to working with decentralized design and manufacturing firms, the technology supplier may work with an integrated IDM that both designs and manufactures the product. Similar to the NSC model, in the integrated supply chain model, the IDM has private information about its design capability. The technology supplier has a prior belief that the capability is high with probability β and low with probability $1-\beta$. As in NSC models, the inverse demand curve is $p = A_H - q$ for the high type and $p = A_L - q$ for the low type, where $A_H > A_L > 0$. Without loss of generality, the per-unit production cost and fixed cost for the IDM are normalized to zero.

In the integrated model, the technology supplier first proposes a license (or a menu of licenses) composed of a per-unit royalty and a one-time licensing fee to the IDM, who then decides whether to accept the technology supplier's offer and if so, which license to choose. If the IDM accepts a license from the technology supplier, it then decides the selling quantity (or equivalently, the selling price) of the product. The technology supplier's optimal licensing strategy is summarized in the following proposition.

Proposition 5. *In an integrated supply chain,*

- *if* $\gamma \in (0, \bar{\gamma}(\beta))$*, where* $\bar{\gamma}(\beta)$ *is given in Lemma 2, then the technology supplier's optimal licensing strategy is high-type-only, and the optimal royalty is* $r_H^{IH} = 0$*;*
- *if* $\gamma \in [\bar{\gamma}(\beta), 1)$*, then the technology supplier's optimal licensing strategy is separating, and the optimal royalties are* $r_H^{IS} = 0$ *and* $r_L^{IS} = (\beta A_H - \beta A_L)\,/\,(1-\beta)$*.*

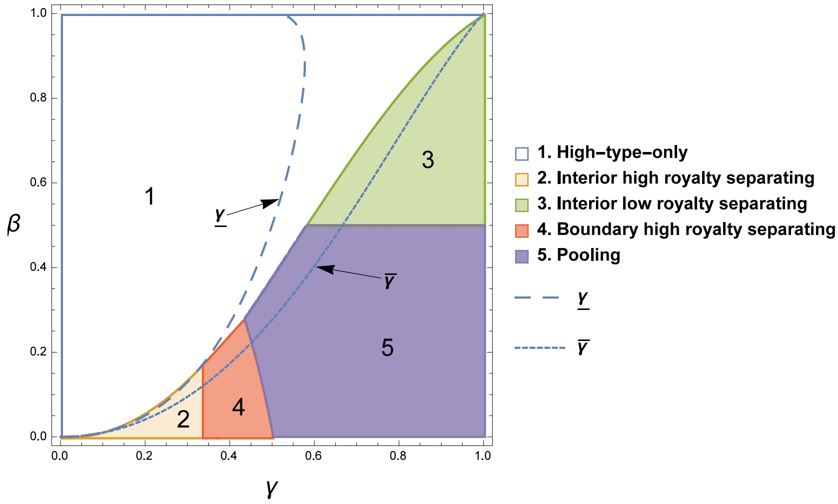
When using the high-type-only strategy, the technology supplier uses the one-time licensing fee F_H to extract all the supply chain profit. Both types of IDMs receive zero profit. Under the optimal separating strategy, the low-type IDM earns zero profit, but the high type earns a positive profit equal to the information rent paid by the technology supplier. In addition, as discussed after Proposition 1, it is always optimal in such a vertical supply chain to set $r_H = 0$ to eliminate the double marginalization problem when facing a high-type firm.

5.2. Comparisons

The NSC models differ from the integrated model in their supply chain structures. Having a third-party manufacturer complicates the technology supplier's problem and raises new issues when determining the optimal licensing strategy. Figure 5 summarizes the technology supplier's optimal licensing strategy in all three supply chain models.

First, we take the technology supplier's perspective and analyze how its optimal licensing strategy depends on the supply chain structure. We then focus on profits and study which party benefits from a more decentralized downstream industry. Because our answers depend on whether the design license is observable in the NSC model, we offer comparisons based on the observability of the design license.

Figure 5 **The Technology Supplier's Optimal Strategy in all Three Supply Chain Models**



Note. Shaded regions represent the technology supplier's optimal strategy in the NSC model with observable design license; $\underline{\gamma}$ is the threshold separating the high-type-only strategy and the separating strategy in the NSC model with confidential design license, and $\bar{\gamma}$ is the parameter threshold that separates the high-type-only strategy and the separating strategy in the integrated supply chain model.

5.2.1. NSC Model with Observable Design License versus Integrated Model The technology supplier's optimal licensing strategy differs considerably in these two technology supply chain models, as we discuss after Proposition 1. Figure 5 also shows that the technology supplier is more likely to use the high-type-only strategy in the integrated supply chain. Furthermore, with respect to the license offered to the high type, the royalty is higher and the licensing fee is lower in the NSC model than in the integrated model. Therefore, in the NSC model, the technology supplier relies more on the royalty and less on the licensing fee to collect profit from the high-type downstream firm.

Which supply chain model is more desirable for the technology supplier when the design license is observable? Does the downstream firm gain more profits in the NSC model? We answer these questions in the following proposition.

Proposition 6. *When the design license is observable to the manufacturer:*

- *The technology supplier's profit is lower in the NSC model than that in the integrated model;*
- *The total downstream expected profit (including the manufacturer's and the design firm's profits) in the NSC model is equal to, higher than, and lower than that in the integrated model for* $\gamma \in (0, \hat{\gamma}(\beta)]$, $\gamma \in (\hat{\gamma}(\beta), \bar{\gamma}(\beta)]$, *and* $\gamma \in (\bar{\gamma}(\beta), 1)$, *respectively.*

Proposition 6 shows that the fragmentation of the downstream industry hurts the technology supplier. In the NSC model, the relationship between the manufacturer and the design firm is based on a wholesale price that creates inefficiency. Furthermore, this inefficiency prevents the technology supplier from lowering royalties to improve efficiency.

That said, decentralization can either improve or weaken the downstream industry's performance, depending on market conditions. In both supply chain models, the low-type IDM or design firm always obtains zero profit. In the NSC model, the manufacturer's expected profit is zero because the technology supplier uses the licensing fee to extract all its expected profit. Thus, comparing the total downstream profit is the same as comparing the high-type firm's profit. When the technology supplier uses the inclusive strategy, the high-type firm is able to keep some information rent. When the market potential ratio is low (i.e., $\gamma \in (0, \hat{\gamma}(\beta)]$), the technology supplier uses the high-type-only strategy, and the downstream profit is zero in both supply chain models. When the market potential ratio is high (i.e., $\gamma \in (\bar{\gamma}(\beta), 1)$), the technology supplier uses the inclusive strategy in both supply chain models, and the downstream profit is lower in the NSC model than in the integrated model. When the market potential ratio is intermediate (i.e., $\gamma \in (\hat{\gamma}(\beta), \bar{\gamma}(\beta)]$), the technology supplier adopts the high-type-only strategy in the integrated model, but uses the inclusive strategy in the NSC model. In this case, the high-type downstream firm and also the whole downstream industry obtain a positive profit in the NSC model but zero profit in the integrated model.

The above discussion helps explain why some IDMs choose to spin off their manufacturing capacity to focus on design and development. A well-known advantage of the NSC model to the downstream firms is the increased utilization of the expensive manufacturing capacity by pooling demand from multiple design firms. Our model presents an additional reason for the unbundling of the IDM as we focus on technology-licensing decisions instead of capacity issues: Switching from the integrated model to the NSC model may change the technology supplier's optimal licensing strategy and thereby increase the downstream firm's profit.

5.2.2. NSC Model with Confidential Design License versus Integrated Model In the confidential NSC, the pooling strategy is never optimal for the technology supplier and $r_H = 0$ always holds, which is the same as that in the integrated model. However, Figure 5 illustrates that the technology supplier is more likely to use the separating strategy in the

NSC model than in the integrated model. In addition, despite the similarity with respect to the technology supplier's strategy, the different supply chain structures still significantly affect profits, as stated in the following proposition.

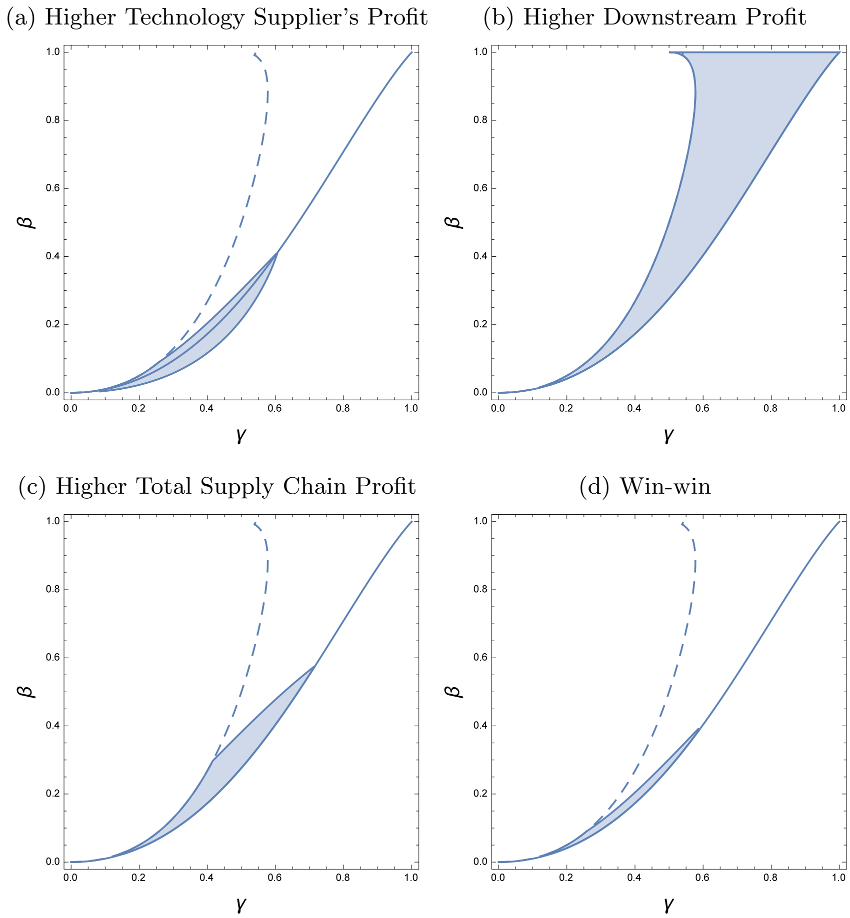
Proposition 7. *In an NSC model with confidential design license:*

- *The technology supplier's profit is strictly higher than that in the integrated model if and only if $\beta < b_0$ and $\gamma_1(\beta) < \gamma < \gamma_2(\beta)$, where b_0 is a constant, $\gamma_1(\beta)$ and $\gamma_2(\beta)$ are threshold functions satisfying $\gamma_1(\beta) \leq \bar{\gamma}(\beta) < \gamma_2(\beta)$ when $\beta < b_0$, as shown in Figure 6(a).*
- *The total downstream expected profit in the NSC model is equal to, higher than, and lower than that in the integrated model for $\gamma \in \left(0, \underline{\gamma}(\beta)\right]$, $\gamma \in \left(\underline{\gamma}(\beta), \bar{\gamma}(\beta)\right]$, and $\gamma \in (\bar{\gamma}(\beta), 1)$, respectively. The region where the downstream profit is higher in the NSC model is shown in the shaded area in Figure 6(b).*
- *The total supply chain profit is higher than that in the integrated model if and only if $\gamma \in \left[\underline{\gamma}(\beta), \bar{\gamma}(\beta)\right]$ and $\beta \leq \beta_3(\gamma)$, as shown in Figure 6(c).*
- *The NSC model results in a win-win situation compared with the integrated model if and only if $\beta < b_0$ and $\gamma_1(\beta) < \gamma < \bar{\gamma}(\beta)$, as shown in Figure 6(d).*

When γ is low (i.e., $\gamma \in \left(0, \underline{\gamma}(\beta)\right]$), the technology supplier uses the high-type-only strategy in both supply chain models, and thus the downstream profit is always zero. When using the high-type-only strategy, the technology supplier charges zero royalty in the integrated model and maximizes the total supply chain profit. In contrast, in the NSC model, the total supply chain profit is not maximized because the manufacturer still charges a positive wholesale price. Since the technology supplier collects the entire supply chain profit when using the high-type-only strategy, both the technology supplier's profit and the total supply chain profit are lower in the NSC model.

When γ is intermediate (i.e., $\gamma \in \left(\underline{\gamma}(\beta), \bar{\gamma}(\beta)\right]$), the technology supplier uses the high-type-only strategy in the integrated model, which maximizes the total supply chain profit in the high-demand case, and leaves zero profit to the downstream firm. In the NSC model, the technology supplier uses the separating strategy, and the high-type design firm obtains a positive information rent. From the whole supply chain perspective, though the total supply chain profit is not maximized for the high-demand case, the supply chain generates positive profit for the low-demand case. If the probability of the high type is low (i.e., $\beta \leq \beta_3(\gamma)$), then the benefit of collecting profit for the low-demand case dominates the loss

Figure 6 Regions Where the NSC Model with Confidential Design License Outperforms the Integrated Model



Note: The NSC model is superior in the shaded areas. The dashed and solid lines are $\bar{\gamma}(\beta)$ and $\underline{\gamma}(\beta)$, respectively.

of efficiency for the high-demand case; thus, the NSC model leads to a higher total supply chain profit. In addition, if γ is relatively large in this region (i.e., $\gamma_1(\beta) \leq \gamma \leq \bar{\gamma}(\beta)$), the difference between the low demand and the high demand is relatively small. Then when we compare the technology supplier's profit in the NSC model with that in the integrated model, the profit gained from the low-type design firm outweighs the profit loss from the high type. Therefore, the technology supplier's profit is higher in the NSC model, and hence the NSC model yields a win-win situation for both the technology supplier and the downstream firm.

When γ is high (i.e., $\gamma \in (\bar{\gamma}(\beta), 1)$), the technology supplier uses the separating strategy in both supply chain models. The downstream profit is lower in the NSC model. The technology supplier's profit is higher in the NSC model if and only if $\bar{\gamma}(\beta) \leq \gamma \leq \gamma_2(\beta)$. However, the total supply chain profit is always lower in the NSC model.

Overall, when the market potential difference is intermediate, the NSC structure induces the technology supplier to use the inclusive strategy instead of the high-type-only one, which benefits the downstream industry. If the downstream firm is more likely to be of low capability, then the gain from the low type dominates, and both the technology supplier and the whole supply chain also benefit from the NSC structure.

Collectively, these results show that the NSC model with confidential design license can benefit both the technology supplier and the downstream firms and lead to a win-win outcome, especially when the market potential difference is intermediate and the probability of high-type design firm is low. These results also suggest another advantage of the NSC model besides the obvious benefit of pooling manufacturing capacity, and help explain the recent rise of the NSC model in technology-intensive industries.

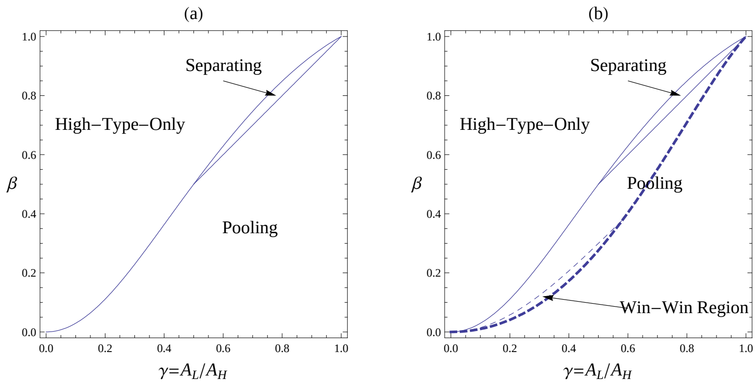
In an NSC, the design firm may or may not be willing to keep the design license confidential. If the design firm can obtain a higher profit by keeping the license confidential, then confidentiality can be achieved, as long as the technology supplier can commit to its own behavior. The following proposition describes the conditions under which the NSC outperforms the integrated model, and the design firm is also willing to keep the license confidential.

Proposition 8. *In an NSC model with confidential design license:*

- *the technology supplier's profit is strictly higher than that in the integrated model, and the confidentiality of the design license also benefits the design firm if and only if* $\beta < b_0$ *and* $\max\{\gamma_1(\beta), \gamma_3(\beta)\} < \gamma < \gamma_2(\beta)$*, where* $\gamma_3(\beta) = \frac{\beta(4\beta^2+5\beta-8)}{4\beta^3-3\beta^2+12\beta-8}$*;*
- *the NSC model results in a win-win situation compared with the integrated model, and the confidentiality of the design license also benefits the design firm if and only if* $\beta < b_0$ *and* $\max\{\gamma_1(\beta), \gamma_3(\beta)\} < \gamma < \bar{\gamma}(\beta)$*.*

These results reveal that even if the technology supplier does not require the design firm to accept the confidentiality term, the design firm may still voluntarily do so; in turn, the NSC model can lead to a higher technology supplier's profit as well as a win-win situation, when compared with the integrated model. In such cases, as long as the technology supplier can credibly commit to the manufacturer, the NSC outperforms an integrated model.

Figure 7 Licensing Strategy with the Design License Determined First and Observable



6. Extensions

6.1. Design License First

When we analyze NSCs in our main model, we assume–based upon observed practice (e.g., ARM's Foundry Program)–that a manufacturer is licensed before a design firm. To understand how our results change if the licensing sequence is altered, we characterize the equilibrium outcome in this section with the design license determined first. If the design license is confidential, then the equilibrium results remain the same, because the technology supplier's design license decision and the manufacturer's wholesale price decision form a simultaneous-move game, and the interaction is independent of the fixed-fee manufacturing license. However, if the design license is observable, then the equilibrium outcome will change. We next focus on this latter case.

Given a design license (r, F), the manufacturer's wholesale price decision and the design firm's quantity decision remain the same as in the manufacturing-license-first case. In short, the analysis in Section 4.1.1 carries over. Anticipating these results, the technology supplier sets $F_M^i(r) = (A_i - r_i)^2/8$, $i = H, L$ to make the manufacturer break even.

Next, we consider the technology supplier's design license problem. A key feature of the design-license-first case is that the manufacturer license is not sunk, and the technology supplier's objective function accounts for the income from the manufacturing license. For instance, the technology supplier's objective function under the inclusive strategy is $\beta\left(r_H q_H\left(r_H\right) + F_H + F_M^H(r_H)\right) + (1-\beta)\left(r_L q_L\left(r_L\right) + F_L + F_M^L(r_L)\right)$.

We compare the technology supplier's profit under the inclusive strategy with that under the high-type-only strategy, and derive its optimal strategy (please refer to Proposition A.1 in the Appendix for detailed mathematical expressions) as illustrated in Figure 7(a). Once again, both separating and pooling can serve as the optimal inclusive strategy. In Figure 7(b), the thick dashed curve separates the high-type-only strategy and separating strategy in the integrated model. Figure 7(b) clearly shows a region where it is optimal to use the high-type-only strategy in the integrated model, but optimal to use the pooling strategy in the NSC model. Since the downstream firm earns zero profit under the high-type-only strategy but a positive profit under the pooling strategy due to the information rent, the downstream firm is better off with a decentralized structure in the NSC model in this region. In addition, when the design license is determined first, the technology supplier obtains a higher profit by keeping the design license confidential in this parameter region, $\{(\gamma,\beta):\max[\frac{\beta+2\sqrt{\beta(1-\beta)^3}}{4-5\beta+2\beta^2},\frac{\beta(2\beta-1)+(2-\beta)\sqrt{(1-\beta)\beta}}{2(1-\beta+\beta^2)}]\leq\gamma\leq\frac{\beta(7-6\beta)}{\max[4-\beta(3+2\beta),0]}\}$.

Finally, because the equilibrium outcome in an NSC with confidential design license does not depend on whether the manufacturer is engaged before or after the design firm, all our results in Section 5.2.2–including the result that the NSC can benefit all parties–remain the same.

6.2. Revenue-based Royalties

In the main model, we assume that the royalty is based on the sales quantity. Once the design license is fixed, the royalty per unit is also fixed and invariant with respect to the product price. In this section, we discuss the case in which the royalty is based on the design firm's (or IDM's) revenue, and is therefore contigent on product price. In such a case, the royalty in the design license is specified as a percentage of the product price. Furthermore, we can no longer normalize the per-unit production cost to zero.

If the per-unit production cost is zero, then using royalties based on sales revenue would eliminate the distortion completely. In both the NSC and integrated models, the technology supplier can simply charge a royalty of 100% of the end product price to extract all the profits from the downstream design firm (or IDM). The supply chain will be coordinated, and the technology supplier can always capture all the supply chain profits.

If there is a positive per-unit production cost, denoted as c_M, then using royalties based on sales revenue cannot eliminate the quantity distortion at the manufacturing/sales stage. Using the integrated supply chain model as an example, if a type i ($i=H,L$) IDM takes a license with a licensing fee F and a royalty rate r (r is the percentage of revenue requested by the technology supplier) from the technology supplier, then its profit maximization problem is $\max_q\left(\left(A_i-q\right)(1-r)-c_M\right)q-F$, and the optimal quantity is $\frac{(1-r)A_i-c_M}{2(1-r)}$. However, if the supply chain is fully integrated, then the optimal quantity is $\frac{A_i-c_M}{2}$. Clearly, the quantity decision with royalties is different from the supply chain optimal quantity, and the quantity distortion remains as long as the royalty rate is non-zero. With positive per-unit production cost, closed-form solutions of models using revenue-based royalties cannot be achieved. To test the robustness of our main results, we have also conducted extensive numerical studies and confirm that our main results still hold, even if the technology supplier uses revenue-based royalties. In particular, there exist parameter sets (e.g., $A_H=3.52,\ A_L=1.6,\ c_M=0.6$, and $\beta=0.2$) such that the NSC with confidential design license leads to a higher total supply chain profit than the integrated model, the downstream firm's expected profit is higher in the NSC, and the technology supplier prefers to keep the design license confidential in the NSC.

6.3. Nonnegative Licensing Fee

In the analysis for the NSC model with observable design license, we find that the licensing fee in the high-royalty separating strategy is negative. This means that the technology supplier subsidizes the design firm upfront, and collects the royalty payment from the design firm later. One may wonder how the results will change if restricting licensing fee to be nonnegative. We address this question by adding the constraints of $F_H, F_L \geq 0$ to the technology supplier's mechanism design problem in (4a)-(4e).[6] That is, the problem to derive the optimal inclusive strategy under the NSC model with observable design license and nonnegative licensing fee can be written as follows:

$$
\begin{gathered}
\max \beta r_H q_H^o\left(r_H\right)+(1-\beta)\, r_L q_L^o\left(r_L\right)+\beta F_H+(1-\beta)\, F_L \\
\text{s.t. IRH: } \pi_H^o\left(r_H, F_H\right)=\left(A_H-r_H\right)^2/16-F_H \geq 0 \text{ and } r_H \leq A_H \\
\text{IRL: } \pi_L^o\left(r_L, F_L\right)=\left(A_L-r_L\right)^2/16-F_L \geq 0 \text{ and } r_L \leq A_L \\
\text{ICH: } \pi_H^o\left(r_H, F_H\right) \geq \pi_H^o\left(r_L, F_L\right)=\left(A_H-r_L\right)^2/16-F_L \\
\text{ICL: } \pi_L^o\left(r_L, F_L\right) \geq \pi_L^o\left(r_H, F_H\right)=\left(A_L-r_H\right)^2/16-F_H, \text{ or } r_H \geq A_L \\
F_H, F_L \geq 0
\end{gathered}
$$

[6] The nonnegative licensing fee constraints only affect the NSC with observable design license, because licensing fees are always nonnegative in the NSC with confidential design license even without such constraints.

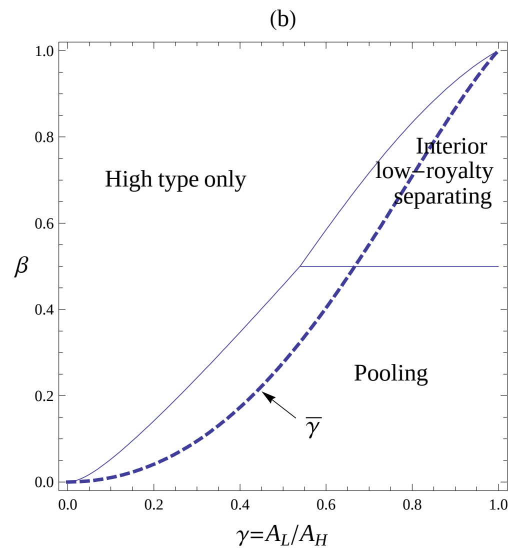


Figure 8 **The Technology Supplier's Optimal Strategy in the NSC Model with Observable Design License and Nonnegative Licensing fee Constraint**

By analyzing the constraints, we find that if the ICL constraint is satisfied by $r_H \geq A_L$, then the rest constraints will lead to $r_H = r_L = A_L$, and $F_L = F_H = 0$. In this case, the low-type design firm's selling quantity is zero and the technology supplier gets zero profit from the low type. Then the inclusive strategy is dominated by the high-type-only strategy. Therefore, the ICL constraint satisfied by $r_H \geq A_L$ can never be optimal for the technology supplier in the presence of constraint $F_H, F_L \geq 0$.

Then we only need to consider the ICL constraint to be satisfied by $\pi_L^o(r_L, F_L) \geq \pi_L^o(r_H, F_H)$, which leads to $r_H \leq r_L$. Following similar analysis as before, we can characterize the technology supplier's optimal licensing strategy, as shown in Figure 8, with the solid lines separating the three regions of optimal policy: High-type-only, interior low-royalty separating, and pooling. The detailed proofs are relegated to the Appendix. Due to the presence of the nonnegative licensing fee constraint, the key difference from the case without the constraint shown in Figure 3 is the replacement of the high-royalty separating strategy in region 2 and 4 of Figure 3(b) by the pooling strategy (the boundary between the high-type-only strategy and the inclusive strategy also changes slightly).

Without the nonnegative licensing fee constraint, the comparison between the NSC model with observable design license and the integrated model is presented in Proposition 6. Our study shows that the presence of the nonnegative licensing fee constraint does not change the qualitative comparison results. For the downstream firm, there still exists a region where the inclusive strategy is used under the NSC model with observable design license, which gives the downstream firm positive expected profits, but the high-type-only strategy is used under the integrated model (the dashed line in Figure 8 is the boundary separating the high-type-only strategy and the separating strategy). In this region, the downstream firm is better off under the NSC model than under the integrated model.

7. Concluding Remarks

In this paper, we study the emerging networked technology supply chains in the presence of information asymmetry. In particular, we examine the technology supplier's optimal licensing strategy in such NSCs, and show that making the design license observable (or not) to the manufacturer has a profound impact on each party's optimal decisions and profits. If the design license is observable to the manufacturer, then the technology supplier's optimal licensing strategy presents several unique features, when compared with that in the traditional vertical supply chain. Specifically, pooling can be the optimal strategy; the royalty in the high-type license is always positive, and can be either higher or lower than that in the low-type license in the separating strategy. In contrast, if the design license is confidential, then similar to the result in the traditional vertical supply chain, pooling is never the optimal strategy, and the technology supplier should charge a zero royalty to the high-type design firm. These results highlight why and how technology suppliers like ARM should customize design licenses based on supply chain structure. To the best of our knowledge, this paper is the first to offer high-level guidelines on how to set licenses to maximize profit in NSCs. Furthermore, our results also demonstrate the importance of incorporating other value-added tasks, such as design, besides the traditional production and inventory decisions, in studying "modern" supply chains.

In addition to these different licensing strategies, the confidentiality of the design license also affects profits. Specifically, we find that the technology supplier's profit is higher if the design license is confidential. However, in some cases, the design firm may have an incentive to reveal the design license to the manufacturer. Even the technology supplier itself, after collecting the licensing fee from the manufacturer, may be tempted to reveal its design license to the manufacturer so as to indirectly affect the manufacturer's wholesale price. Such challenges in achieving confidentiality in an NSC–absent in a vertical supply chain–suggest that technology suppliers such as ARM should commit up front to keeping the design license confidential, if the suppliers wish to levy the benefit of confidentiality; moreover, suppliers should specify as much in written contracts with design firms to ensure enforcement.

Crucially, we find that the networked supply chain differs from the traditional vertical supply chain model in firms' profits and performance. We show that if the design license is observable in the NSC model, then the technology supplier's profit is actually lower in the NSC model where the downstream industry is decentralized. However, the downstream profit can be higher in the NSC model, which indicates that an IDM would gain more profits by spinning off its manufacturing capacity and becoming a pure design firm. If the design license is confidential, then we find that the NSC model can lead to higher profits for both the technology supplier and the design firm, yielding an overall win-win situation, when compared to the integrated model. These results provide one possible rationale for an IDM, such as AMD, to spin off its manufacturing part to become a pure design firm. Furthermore, our analysis shows that such decentralization is more beneficial for the downstream firm when the market potential difference is intermediate.

Our research is motivated by a major new supply chain structure pioneered by ARM in the semiconductor industry. Such NSCs require not only that technological advances drive supply chain progress, but also that design and manufacturing knowledge are fairly explicit and codified. As other technology industries become more and more mature in new product development and manufacturing, we may see such NSCs emerge as well. For example, in the biotechnology industry, technology is a crucial factor, but manufacturing knowledge has historically been highly tacit and coupled to the design of the product. However, the emergence of contract pharmaceutical and biotech manufacturers[7], such as Wockhardt and Wuxi, and codification of biotech manufacturing (The Medicine Maker 2016) in the last few years raises the possibility of NSCs similar to the one studied in this paper. In summary, as technology industries (such as the biotechnology industry) mature their design and manufacturing functions, we conjecture that they would also develop networked supply chains. Our analysis can provide guidance on whether and how they should form such NSCs.

[7] For a list of biopharmaceutical contract manufacturers, please see `http://www.hightechdecisions.com/industry_bioman.html`.

The NSC structure that is emerging in several industries (e.g., semiconductors, automotives, life sciences) requires an intricate licensing approach and information disclosure strategy, and deserves further research attention due to its superior performance. This study on NSCs also offers several new directions for future research. First, in our NSC model, there is one technology supplier. It may be worthwhile to study how competition can affect the technology supplier's optimal licensing strategy and firms' profits. Second, since both the NSC model and the integrated model can co-exist and compete in practice, it will be interesting to study competition between supply chains. Third, this research focuses on the technology supplier's licensing strategy and the information asymmetry on the design firm's capability. However, when introducing new electronic products, the manufacturer may also have to exert significant process development effort, whose outcomes are uncertain. Incorporating the manufacturer's development effort, beyond the scope of this paper, should be a topic of future work as it can generate new insights. Finally, our theoretical results can potentially be empirically validated in the emergence and growth of networked supply chain in more technology-driven industries. For example, our results indicate that the downstream firm gets a higher profit in the NSC model than the integrated supply chain model when the probability of high demand is intermediate. As a result, as a new technology-driven industry emerges, it has a low market size at the beginning and hence integrated supply chain model is expected. But as the market size grows to a certain level, i.e., the probability of high demand for newly developed products increases to a certain magnitude, networked supply chains are likely to emerge.

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Appendix

Proof of Lemma 1. First, constraint (4b) is satisfied if constraints (4c) and (4d) are satisfied, because $\pi_H^O(r_H, F_H) \geq \pi_H^O(r_L, F_L) > \pi_L^O(r_L, F_L) \geq 0$. And constraint (4d) should be binding, because otherwise the supplier can increase F_H to increase profit. In addition, constraint (4c) should be binding, because otherwise the supplier can increase F_L and F_H simultaneously to increase profit. By solving the two binding constraints we have: $F_L = \left(\frac{A_L - r_L}{4}\right)^2$, and $F_H = \left(\frac{A_H - r_H}{4}\right)^2 - \left(\frac{A_H - r_L}{4}\right)^2 + \left(\frac{A_L - r_L}{4}\right)^2$.

Substituting them into the objective function (4a) gives us the new objective function Π^{OI} as given in equation (6). Simplifying constraint (4e) gives us the constraint $r_H \leq r_L$ or $r_H \geq A_L$. □

LEMMA A.1. *In the NSC model with observable design license:*

- *when $\beta \in \left[\frac{2\gamma}{1+\gamma}, 1\right)$, the inclusive strategy is dominated by the high-type-only strategy;*
- *when $\beta \in \left(1/2, \frac{2\gamma}{1+\gamma}\right)$, the technology supplier's optimal inclusive strategy is interior low-royalty separating;*
- *when $\beta \in \left(0, \min\left\{1/2, \frac{2\gamma}{1+\gamma}\right\}\right]$, the technology supplier's optimal inclusive strategy changes from interior high-royalty separating, to boundary high-royalty separating, and finally pooling as γ increases.*

The optimal royalties are:

- *$r_L^{OS} = \frac{(1-2\beta)A_L + \beta A_H}{3(1-\beta)}$, and $r_H^{OS} = \frac{A_H}{3}$ in both interior high-royalty and low-royalty separating strategies;*
- *$r_H^{OB} = A_L$ and $r_L^{OB} = r_L^{OS}$ in the boundary high-royalty separating strategy;*
- *$r_H^{OP} = r_L^{OP} = \frac{A_L + 2\beta(A_H - A_L)}{3}$ in the pooling strategy.*

Proof of Lemma A.1. We maximize over r_L and r_H in the two feasible regions to maximize the technology supplier's expected profit Π^{OI}. First, we analyze the optimal r_L and r_H of the unconstrained problem and then check whether the resulting optimal solution falls in the feasible regions. Taking the first and the second order derivatives of Π^{OI} as given in (6) with respect to r_L and r_H,

We can verify that Π^{OI} is jointly concave in both r_L and r_H. And solving the first-order conditions, we have r_L^{OS} and r_H^{OS} as given in Lemma A.1. Substituting them back we have

$$\Pi_T^{OS} = \frac{-A_H^2\beta + 2A_H A_L \beta(2\beta - 1) + A_L^2\left(-4\beta^2 + 7\beta - 4\right)}{48(\beta - 1)} \tag{A.1}$$

We then study when (r_L^{OS}, r_H^{OS}) fall in the feasible regions.

First, $r_H^{OS} = A_H/3 < A_H$.

Second, $r_L^{OS} \leq A_L$ if and only if $\beta \leq \frac{2A_L}{A_H + A_L}$. Therefore, when $\beta \geq \frac{2A_L}{A_H + A_L}$, $r_L^{OS} \geq A_L$, the optimal inclusive strategy requires $r_L = A_L$, in which case the low-type's selling quantity is zero and the technology supplier gets zero profit from the low type. In this case, the inclusive strategy is dominated by the high-type-only strategy.

Third, $r_H^{OS} \leq r_L^{OS}$ if and only if $\beta \geq \frac{1}{2}$.

Forth, $r_H^{OS} \geq A_L$ if and only if $\gamma \leq 1/3$.

To summarize, there are two thresholds for β and one threshold for γ. We can further verify that $\frac{2A_L}{A_H + A_L} \leq \frac{1}{2}$ if and only if $\gamma \leq 1/3$. So there are six possible cases based on the parameters:

Case 1:	$\gamma \leq 1/3$	Case 2:	$\gamma > 1/3$
Case 1.1:	$\beta < \frac{2A_L}{A_H + A_L}$	Case 2.1:	$\beta \leq \frac{1}{2}$
Case 1.2:	$\frac{2A_L}{A_H + A_L} \leq \beta < \frac{1}{2}$	Case 2.2:	$\frac{1}{2} < \beta < \frac{2A_L}{A_H + A_L}$
Case 1.3:	$\beta \geq \frac{1}{2}$	Case 2.3:	$\beta \geq \frac{2A_L}{A_H + A_L}$

Next, we analyze all six possible cases. In cases 1.2, 1.3, and 2.3, $\beta \geq \frac{2A_L}{A_H + A_L}$ and thus the inclusive strategy is dominated by the high-type-only strategy. In case 1.1, $r_H^{OS} > A_L$ and $r_L^{OS} < A_L$, so $\{r_L^{OS}, r_H^{OS}\}$ falls in region I and is the optimal solution. In case 2.2, $r_H^{OS} < r_L^{OS}$ and $r_L^{OS} < A_L$, so $\{r_L^{OS}, r_H^{OS}\}$ falls in feasible region (low-royalty separating) and is the optimal solution. Case 2.1 needs further investigation.

In case 2.1, the first-order solution (r_L^{OS}, r_H^{OS}) falls in the infeasible region. Since Π^{OI} is jointly concave in r_L and r_H, the global optimal (r_L, r_H) fall on either the boundary high-royalty separating or pooling.

If the boundary high-royalty separating is used, then $r_H = A_L$, and $r_L = r_L^{OS}$. Substituting the two expressions into the technology supplier's and manufacturing firm's expected profits, we derive the technology supplier's optimal profit as

$$\Pi_T^{OB} = \frac{1}{48(1-\beta)} \left(\beta^2 A_H^2 + 2\beta(4-5\beta) A_H A_L + \left(4 - 16\beta + 13\beta^2\right) A_L^2\right) \tag{A.2}$$

and the manufacturing firm's expected profit as

$$\pi_M^{OB} = \frac{\beta}{8}(A_H - A_L)^2 + \frac{(A_L(-2+\beta) + A_H \beta)^2}{72(1-\beta)} - F_M. \tag{A.3}$$

If the pooling strategy is used, we have $r_L = r_H = r$. Substituting it in Π^{OI}, and taking the derivative of Π^{OI} with respect to r, and solving the first-order condition $\frac{\partial \Pi^{OI}}{\partial r} = 0$ leads to

$$r_H^{OP} = \frac{A_L + 2\beta(A_H - A_L)}{3} \leq A_L, \tag{A.4}$$

Because $A_L \geq \frac{A_H}{3}$ and $\beta \leq \frac{1}{2}$ in case 2.1, we can verify that $(A_L + 2\beta(A_H - A_L))/3 \leq A_L$. So it is optimal in the pooling strategy. And the corresponding optimal pooling profit for the technology supplier is

$$\Pi_T^{OP} = \frac{1}{12}\left(\beta^2 A_H^2 + \left(1 - \beta + \beta^2\right) A_L^2 + \beta(1-2\beta) A_H A_L\right) \tag{A.5}$$

and the expected profit for the manufacturing firm is

$$\pi_M^{OP} = \frac{1}{72}\left(\beta(9-8\beta) A_H^2 + \left(4 + 5\beta - 8\beta^2\right) A_L^2 + 2\beta(-7+8\beta) A_H A_L\right) - F_M. \tag{A.6}$$

We compare the technology supplier's profit under the boundary high-royalty separating strategy Π_T^{OB} with that under the pooling strategy Π_T^{OP} and find the conditions under which each strategy is optimal.

Summarizing the conditions and the results follow. □

Proof of Proposition 1. The optimal high-type-only strategy is presented in the following Lemma.

LEMMA A.2. *In the NSC model with observable design license, the technology supplier's optimal high-type-only license strategy is* $(r_H^{OH} = A_H/3, F_H^{OH} = A_H^2/36)$*, and the corresponding profit is* $\pi_T^{OH} = 5\beta A_H^2/36$.

Proof of Lemma A.2. It is optimal to set the constraint binding, i.e., $\pi_H^O(r_H, F_H) = (A_H - r_H)^2/16 - F_H = 0$. Then substituting $F_H = (A_H - r_H)^2/16$ into the objective function, we have $\beta q_H^O(r_H) r_H + \beta F_H = \beta\left(r_H(A_H - r_H)/4 + (A_H - r_H)^2/16\right)$, which is a concave function. Solving the first-order condition gives us $r_H^{OH} = A_H/3$. Because $r_H^{OH} < A_H$, it is the optimal solution. Substituting r_H^{OH} back gives us F_H^{OH} and π_T^{OH} as presented in the lemma. □

If $\beta \geq \frac{2A_L}{A_H+A_L}$, the optimal strategy for the technology supplier is the high-type-only strategy. If $\beta < \frac{2A_L}{A_H+A_L}$, in order to derive the technology supplier's optimal licensing strategy, we need to compare its profit under the high-type-only strategy with that under the inclusive strategy.

Based on the comparison results (the detailed derivations are omitted here but available from the authors upon request) and the result that the high-type-only strategy is optimal for the technology supplier for $\beta \geq \frac{2A_L}{A_H+A_L}$, we summarize the technology supplier's optimal strategy for all possible parameter settings and the results follow.

We also summarize the equilibrium profits as follows. When the technology supplier uses the interior separating strategy, the profis are

$$\pi_T^{OS} = \frac{A_H^2\beta(6\beta-11)+2A_HA_L\beta(4\beta+1)+A_L^2\left(-14\beta^2+29\beta-20\right)}{144(\beta-1)}, \tag{A.7}$$

$$\pi_H^{OS} = \frac{(A_H-A_L)(5A_H\beta-3A_H-A_L\beta-A_L)}{48(\beta-1)}, \tag{A.8}$$

$$\pi_{SC}^{OS} = \frac{A_H^2\beta(21\beta-20)+2A_HA_L\beta(4-5\beta)+A_L^2\left(-11\beta^2+32\beta-20\right)}{144(\beta-1)}. \tag{A.9}$$

When the technology supplier uses the boundary separating strategy:

$$\pi_T^{OB} = \frac{A_H^2\beta(13\beta-18)-10A_HA_L(\beta-2)\beta+A_L^2\left(-23\beta^2+38\beta-20\right)}{144(\beta-1)}, \tag{A.10}$$

$$\pi_H^{OB} = \frac{(A_H-A_L)(5A_H\beta-3A_H-A_L\beta-A_L)}{48(\beta-1)}, \tag{A.11}$$

$$\pi_{SC}^{OB} = \frac{A_H^2\beta(28\beta-27)+2A_HA_L\beta(13-14\beta)+A_L^2\left(-20\beta^2+41\beta-20\right)}{144(\beta-1)}. \tag{A.12}$$

When the technology supplier uses the pooling strategy:

$$\pi_T^{OP} = \frac{1}{72}\left(A_H^2\beta(9-2\beta)+4A_HA_L(\beta-2)\beta-A_L^2\left(2\beta^2+\beta-10\right)\right), \tag{A.13}$$

$$\pi_H^{OP} = -\frac{1}{48}(A_H-A_L)(A_H(4\beta-3)-A_L(4\beta+1)), \tag{A.14}$$

$$\pi_{SC}^{OP} = \frac{1}{144}\left(A_H^2\beta(27-16\beta)+2A_HA_L\beta(16\beta-11)+A_L^2\left(-16\beta^2-5\beta+20\right)\right). \tag{A.15}$$

When the technology supplier uses the high-type-only strategy:

$$\pi_T^{OH} = \frac{5A_H^2\beta}{36}, \tag{A.16}$$

$$\pi_H^{OH} = 0, \tag{A.17}$$

$$\pi_{SC}^{OH} = \frac{5A_H^2\beta}{36}. \quad \square \tag{A.18}$$

Proof of Lemma 2. We first consider the technology supplier's high-type-only strategy. If the technology supplier adopts the high-type-only strategy, it offers a license (r_H, F_H) to attract the high-type design firm only. Considering the high-type design firm's optimal quantity, the technology supplier's problem is as follows:

$$\max_{\{r_H \leq A_H, F_H\}} \beta\left(r_H q_H^C(r_H)+F_H\right)$$
$$\text{s.t. } \pi_H^C(r_H, F_H) \geq 0.$$

By setting the individual rationality constraint binding, we derive $F_H = \left(\frac{A_H - r_H}{2}\right)^2$. Substituting it into the objective function and taking the derivative, we get $-\beta r_H/2 < 0$. Therefore, the technology supplier's optimal licensing term under the high-type-only strategy: $r_H^{CH}(x_H) = 0$, $F_H^{CH}(x_H) = x_H^2/4$. And the technology supplier's optimal profit is $\Pi_T^{CH}(x_H)\beta x_H^2/4$.

We now consider the technology supplier's mechanism design problem under the inclusive strategy.

Similar to the analysis in the NSC model with observable design license, the technology supplier's licensing fees are

$$F_L = \left(\frac{x_L - r_L}{2}\right)^2, \tag{A.19}$$

$$F_H = \left(\frac{x_H - r_H}{2}\right)^2 - \left(\frac{x_H - r_L}{2}\right)^2 + \left(\frac{x_L - r_L}{2}\right)^2. \tag{A.20}$$

And its mechanism design problem can be simplified as

$$\max_{\{r_H \le x_H, r_L \le x_L\}} \Pi_T^{CS}(r_H, r_L) \tag{A.21a}$$

$$\text{s.t. } r_H \le r_L \text{ or } r_H \ge x_L, \tag{A.21b}$$

where

$$\Pi_T^{CI}(r_H, r_L) = \beta r_H q_H^C(r_H) + (1-\beta)\, r_L q_L^C(r_L) + \beta\frac{(x_H - r_H)^2}{4} - \beta\frac{(x_H - r_L)^2}{4} + \frac{(x_L - r_L)^2}{4}. \tag{A.22}$$

Taking derivatives of $\Pi_T^{CS}(r_H, r_L)$, we have $\frac{\partial \Pi_T^{CS}}{\partial r_H} = -\beta r_H/2 < 0$, $\frac{\partial \Pi_T^{CS}}{\partial r_L} = (\beta\,(x_H - x_L) - (1-\beta)\, r_L)$, and Π_T^{CS} is jointly concave in r_L and r_H. Solving the first-order conditions we have $r_H^* = 0$ and $r_L^* = \frac{\beta(x_H - x_L)}{1-\beta}$. By the concavity of Π_T^{CS} in r_L and r_H, considering the optimal (r_L, r_H) must fall into the feasible regions, the optimal solution of the inclusive strategy is $r_H^{CS}(x_L, x_H) = 0$ and $r_L^{CS}(x_L, x_H) = \min\{r_L^*, x_L\}$.

If $\frac{\beta(x_H - x_L)}{1-\beta} \ge x_L$, which is equivalent to $\beta \ge x_L/x_H$, then $r_L^{CS}(x_L, x_H) = x_L$ and hence $q_L = 0$. This means that if $\beta \ge x_L/x_H$, the low-type design firm does not actually sell products, and the technology supplier gets zero profit from the low-type. Therefore, the inclusive strategy is dominated by the high-type-only strategy.

If $\beta < x_L/x_H$, $\frac{\beta(x_H - x_L)}{1-\beta} < x_L$, then

$$r_L^{CS}(x_L, x_H) = r_L^* = \frac{\beta\,(x_H - x_L)}{1-\beta} < x_L, \tag{A.23}$$

$$r_H^{CS}(x_L, x_H) = 0. \tag{A.24}$$

Substituting $r_L^{CS}(x_L, x_H)$ and $r_H^{CS}(x_L, x_H)$ into equations (A.19) and (A.20) gives us $F_L^{CS}(x_L, x_H)$ and $F_L^{CS}(x_L, x_H)$ as follows:

$$F_H^{CS}(x_L, x_H) = \frac{2\beta x_H^2 - 4\beta x_H x_L + (1+\beta)\, x_L^2}{4 - 4\beta}, \tag{A.25}$$

$$F_L^{CS}(x_L, x_H) = \frac{(x_L - x_H\beta)^2}{4\,(1-\beta)^2}. \tag{A.26}$$

Finally, we compare the technology supplier's profit in both the high-type-only strategy and the inclusive strategy. Because the inclusive strategy is dominated by the high-type-only strategy if $\beta \ge x_L/x_H$, we only need to compare the technology supplier's profits in the two strategies for $\beta < x_L/x_H$. If $\beta < x_L/x_H$,

$$\Pi_T^{CS}(x_L, x_H) - \Pi_T^{CH}(x_H) = \frac{x_H^2}{4\,(1-\beta)}\left(\beta^2 - \beta + 1\right)(x_L/x_H)^2 - 2\beta^2(x_L/x_H) + 2\beta^2 - \beta \equiv \frac{x_H^2}{4\,(1-\beta)}\Omega.$$

Denote $\gamma_x = x_L/x_H$. Then it is clear that Ω is convex in γ_x. $\Omega|_{\gamma_x=1} > 0$, $\Omega|_{\gamma_x=\beta} = -\beta(1-\beta)^3 < 0$, So there exist

$$\bar{\gamma}(\beta) = \frac{\beta^2 + (1-\beta)\sqrt{\beta(1-\beta)}}{1-\beta+\beta^2}, \tag{A.27}$$

such that $\bar{\gamma}(\beta) \in (\beta, 1)$, and $\Pi_T^{CS}(x_L, x_H) \geq \Pi_T^{CH}(x_H)$ if and only if $\gamma_x = x_L/x_H \in [\bar{\gamma}(\beta), 1)$. $\square$

Proof of Proposition 2. We first show that there does not exist an equilibrium where $x_H \leq x_L$. We prove by contradictions.

First, we consider the case where $x_H < x_L$. Suppose that there exists an equilibrium such that $x_H < x_L$. Then from the technology supplier's point of view, the low-type now has a higher effective demand. If it only aims at attracting the low-type design firm, it offers a single contract with zero royalty, that is, $r_L = 0$. Then the manufacturing firm's optimal response is $w_L = A_L/2$ by equation (8). Because the manufacturing firm has the belief that the technology supplier offers only one contract, if a high-type design firm indeed asks the manufacturing firm for a quotation, the manufacturing firm believes that the design firm takes $r_L = 0$ and will offer a wholesale price $w_H = A_H/2$ by equation (8). Then $x_H = A_H - w_H = A_H/2 > x_L = A_L - w_L = A_L/2$, which contradicts with $x_H < x_L$. If the technology supplier uses a separating strategy, then reversing L and H, and replacing β with $1-\beta$, we have $r_L = 0$ and $r_H = (1-\beta)(A_L - w_L - A_H + w_H)/\beta$. Solving these two equations together with equation (8), we have the equilibrium outcome as $w_L = A_L/2$ and $w_H = (2A_H - A_L + A_L\beta)/(2+2\beta)$. Then $x_H = A_H - w_H = (A_L + 2A_H\beta - A_L\beta)/(2+2\beta)$, and $x_L = A_L - w_L = A_L/2$. Then $x_H - x_L = (A_L + 2A_H\beta - A_L\beta - A_L - A_L\beta)/(2+2\beta) = \beta(A_H - A_L)/(1+\beta) > 0$, which contradicts with $x_H < x_L$.

We now consider the case where $x_H = x_L$, In an equilibrium where $x_H = x_L$, the two types of design firms are effectively the same from the technology supplier's point of view. So the technology supplier's do not need to solve a mechanism design problem. Instead, its optimal decision is to set the royalty as zero to maximize the efficiency and use the licensing fee to extract all the profits generated by the design firm. Therefore, it must be that $r_L = r_H = 0$, and $F_L = F_H = (A_H - w_H)^2/4$. Then given $r_L = r_H = 0$, the manufacturing firm's optimal wholesale prices are $w_H = A_H/2$ and $w_L = A_L/2$ by equation (8). Then $x_H = A_H - w_H = A_H/2$, $x_L = A_L - w_L = A_L/2$, and thus $x_H > x_L$, which contradicts with $x_H = x_L$.

If $x_H > x_L$ in equilibirum, $r_H = 0$ by Lemma 2. Then the manufacturing firm's optimal wholesale price for the high-type is $w_H = A_H/2$ by equation (8).

If the technology supplier uses a high-type-only strategy, then $F_H = (x_H)^2/4 = (A_H - w_H)^2/4 = A_H^2/16$. For the manufacturing firm's decision on w_L, given that the technology supplier offers a single contract with zero royalty and licensing fee equals to $A_H^2/16$, suppose a low-type design firm did take the contract then ask the manufacturing firm for a quotation, the manufacturing firm's optimal response is $w_L = A_L/2$ by equation (8). Then from the technology supplier's point of view, $x_i = A_i/2$, $i \in \{L, H\}$. Using the result in Lemma 2, the high-type-only strategy is indeed optimal if and only $\beta \geq \underline{\beta}(x_L/x_H)$. Therefore, $r_H^{CH} = 0$, $F_H^{CH} = (A_H)^2/16$, and $w_H^{CH} = A_H/2$, $w_L^{CH} = A_L/2$ is an equilibrium if and only $\beta \geq \underline{\beta}(x_L/x_H)$, which is equivalent to $\gamma \leq \bar{\gamma}(\beta) = (\beta^2 + (1-\beta)\sqrt{\beta(1-\beta)})/(1-\beta+\beta^2)$.

If the technology supplier uses an inclusive strategy, then $r_L = \beta(A_H - w_H - A_L + w_L)/(1-\beta)$, and $r_H = 0$ by Lemma 2. Solving these two equations with equation (8) for $i \in \{L, H\}$ we have, $r_L^{CS} = \beta(A_H - A_L)/(2-\beta)$,

$r_H^{CS}=0$, $w_L^{CS}=(2A_L-\beta A_H)/(4-2\beta)$, and $w_H^{CS}=A_H/2$. Substituting x_i with A_i-w_i, $i=L,H$ in equations (A.26) and (A.25), we have $F_L^{CS}=(\beta A_H-2A_L)^2/(8-4\beta)^2$ and $F_H^{CS}=((8-7\beta)\beta A_H^2-12(1-\beta)\beta A_H A_L+4(1-\beta^2)A_L^2)/(8-4\beta)^2$. In addition, $x_H-x_L=(A_H-A_L)(1-\beta)/(2-\beta)>0$. And $w_L\geq 0$ if and only $2A_L-\beta A_H\geq 0$.

For this to be an equilibrium, we also need to make sure that the inclusive strategy is the technology supplier's optimal strategy given w_L and w_H. By Lemma 2, the inclusive strategy is optimal if and only if $\beta\leq\underline{\beta}(x_L/x_H)$, which simplifies to

$$\frac{\beta A_H-2A_L\beta+2A_L}{4-2\beta}\geq\frac{A_H\left(\beta^2+(1-\beta)\sqrt{(1-\beta)\beta}\right)}{2((\beta-1)\beta+1)}. \tag{A.28}$$

Simplifying $2A_L-\beta A_H\geq 0$ and condition (A.28) together, we have $\gamma\geq\underline{\gamma}(\beta)=(\beta(2\beta-1)+(2-\beta)\sqrt{(1-\beta)\beta})/(2(1-\beta+\beta^2))$.

Comparing $\underline{\gamma}(\beta)$ with $\bar{\gamma}(\beta)$: $\bar{\gamma}(\beta)-\underline{\gamma}(\beta)=\frac{\beta(1-\sqrt{\beta(1-\beta)})}{2(1-\beta+\beta^2)}>0$. Then the results on existence of equilibria follow.

We next compare the two equilibria. Plugging the equilibrium outcomes into the profit functions, we get profits as follows:

In the equilibrium where the technology supplier uses the high-type-only strategy, the technology supplier's profit (not including the licensing fee in the manufacturing license) is

$$\Pi_T^{CH}=\beta A_H^2/16, \tag{A.29}$$

and the manufacturing firm's gross profit (not considering the licensing fee in the manufacturing license) is

$$\Pi_M^{CH}=\beta A_H^2/8. \tag{A.30}$$

In the equilibrium where the technology supplier uses the separating strategy:

$$\Pi_T^{CS}=\frac{A_H^2\beta^2(5-4\beta)+4A_HA_L\beta\left(2\beta^2-3\beta+1\right)-4A_L^2\left(\beta^3-2\beta^2+2\beta-1\right)}{16(\beta-2)^2}, \tag{A.31}$$

$$\Pi_M^{CS}=\frac{A_H^2\beta(4-3\beta)+4A_HA_L(\beta-1)\beta-4A_L^2(\beta-1)}{8(\beta-2)^2}. \tag{A.32}$$

Comparing the profits in both equilibria when $\underline{\gamma}(\beta)\leq\gamma<\bar{\gamma}(\beta)$ and the result follow. □

Proof of Proposition 3. If the design license is observable to the manufacturing firm, the technology supplier's optimal strategies and the associated profits for the technology supplier and the design firm are summarized in Proposition 1 and its proof.

If the design license is confidential, the profits are as follows: When $\gamma<\underline{\gamma}(\beta)$, the technology supplier's profit is $\pi_T^{CH}=3\beta A_H^2/16$.

When $\gamma\geq\gamma_3(\beta)=\underline{\gamma}(\beta)$, the technology supplier's profit is

$$\pi_T^{CS}=\frac{4A_L^2(1-\beta)+A_H^2(4-3\beta)\beta-4A_HA_L(1-\beta)\beta}{8(2-\beta)^2}. \tag{A.33}$$

Comparing the profits in both scenarios and the results follow. □

Proof of Proposition 4. We prove the proposition by contradiction. Suppose the technology supplier violates the confidentiality clause in the manufacturing contract. Then the design license can be revealed to the manufacturer by either the technology supplier itself or by the design firm.

First, suppose it is the technology supplier itself who reveals the design license to the manufacturer. It would do so because it can get additional profit $\Pi_T^O - \Pi_T^C$; but it also means a breach penalty at least $\Pi_T^O - \Pi_T^C$. This implies the technology supplier would be worse off violating the confidentiality agreements.

Second, suppose it is the design firm who reveals the design license to the manufacturer. The design firm would do so only if there is no confidentiality clause in the design license that forbids such behavior. Then the technology supplier would incur a penalty at least $\Pi_T^O - \Pi_T^C$, which is larger than the maximum gain that it can get. This implies the technology supplier would be worse off not imposing the confidentiality clause in the design license. However, being the sole supplier of the technology, the technology supplier is able to impose a confidentiality clause in the design license to prevent the design firm from revealing the design license to the manufacturer.

In summary, given the provisions specified in the proposition, it is incentive compatible for the technology supplier to keep the design license confidential, and to impose a confidentiality clause in the design license to prevent the design firm from revealing. Therefore, the technology suppliers commitment is credible. □

Proof of Proposition 5. The proof is similar to that of Lemma 2 after replacing x_i, $i \in \{L, H\}$ with A_i, $i \in \{L, H\}$. In addition, we can show that $\gamma \geq \bar{\gamma}(\beta)$ if and only if $\beta \leq \underline{\beta}(\gamma)$, where $\underline{\beta}(\gamma) = \frac{1+\gamma^2-(1-\gamma)\sqrt{(1-\gamma)(1+3\gamma)}}{4-4\gamma+2\gamma^2}$. The technology supplier's profit, total supply chain profit, consumer surplus, and social welfare are as follows.

In the integrated model, when the technology supplier uses the separating strategy, the profits are

$$\pi_T^{IS} = \frac{-2A_L(A_H\beta^2) + A_H^2\beta^2 + A_L^2(\beta^2 - \beta + 1)}{4(1-\beta)}, \tag{A.34}$$

$$\pi_H^{IS} = \frac{(A_H - A_L)(3A_H\beta - A_H - A_L\beta - A_L)}{4(\beta - 1)}, \tag{A.35}$$

$$\pi_{SC}^{IS} = \frac{A_H^2\beta(2\beta-1) - 2A_HA_L\beta^2 + A_L^2(2\beta-1)}{4(\beta-1)}. \tag{A.36}$$

When the technology supplier uses the high-type-only strategy, we have

$$\pi_T^{IH} = \frac{A_H^2\beta}{4}, \tag{A.37}$$

$$\pi_H^{IH} = 0, \tag{A.38}$$

$$\pi_{SC}^{IH} = \frac{A_H^2\beta}{4}. \quad \square \tag{A.39}$$

Proof of Proposition 6. For the technology supplier's profit, comparing it under both supply chain models in different conditions and the results follow.

For the downstream profit, because the low-type downstream firm always gets zero profit in both supply chain models, and the manufacturing firm's profit is always zero in the NSC model, comparing the total downstream profit is the same as comparing the high-type downstream firm's profit.

The high-type downstream firm's equilibrium profit in all different cases as shown in equations (A.38), (A.35), (A.8), (A.11), (A.14), and (A.17). Comparing the high-type downstream firm's profit in both supply chain models under different conditions, and the result follows. □

Proof of Proposition 7. In the integrated model, the technology supplier's optimal strategies and the associated profits for the technology supplier and the IDM firm are summarized in Proposition 5 and its proof. In the NSC model, if the design license is confidential, the profits for the technology supplier and the design firm are summarized in the proof of Proposition 3.

- When $\gamma \in \left[0, \underline{\gamma}(\beta)\right]$, the technology supplier uses the high-type-only strategy in both supply chain models. In this region, the downstream profit is always zero in both supply chain models. Comparing the technology supplier's profits in both supply chain models, we have that the technology supplier's profit is always lower in the NSC model. And the total supply chain profit is always lower in the NSC model.
- When $\gamma \in \left[\underline{\gamma}(\beta), \bar{\gamma}(\beta)\right]$, the technology supplier uses the high-type-only strategy in the integrated model, but uses the inclusive strategy in the NSC model. In the integrated model, the downstream profit is zero because the technology supplier uses the high-type-only strategy. But the downstream profit is positive in the NSC model because the high type design firm gets a positive information rent. Comparing the technology supplier's profit we have that the technology supplier's profit is higher in the NSC model if and only if

$$8\beta - 15\beta^2 + 8\beta^3 + (4\beta + 4\beta^2 - 8\beta^3)\gamma + (-12 + 16\beta - 8\beta^2 + 4\beta^3)\gamma^2 \leq 0, \tag{A.40}$$

which is equivalent to

$$\gamma \geq -\frac{-2\beta^3 + \beta^2 - (\beta - 2)\sqrt{\beta\left(-4\beta^3 + 11\beta^2 - 13\beta + 6\right)} + \beta}{2\left(\beta^3 - 2\beta^2 + 4\beta - 3\right)}.$$

Define

$$\gamma_1(\beta) = \max\left\{-\frac{-2\beta^3 + \beta^2 - (\beta - 2)\sqrt{\beta\left(-4\beta^3 + 11\beta^2 - 13\beta + 6\right)} + \beta}{2\left(\beta^3 - 2\beta^2 + 4\beta - 3\right)}, \underline{\gamma}(\beta)\right\}.$$

We can verify that there exists a constant $b_0 \in [0,1]$ such that $\gamma_1(\beta) \leq \bar{\gamma}(\beta)$ if and only if $\beta \leq b_0$. Then in this region, the technology supplier's profit is higher in the NSC model if and only if $\gamma_1(\beta) \leq \gamma \leq \bar{\gamma}(\beta)$. Comparing the total supply chain profit we have that the NSC model leads to a higher total supply chain profit if and only if

$$f(b) = 4b^3y - 12y^2 + b^2(-3 - 8y - 8y^2) + b(4 + 4y + 20y^2) \leq 0.$$

Then $\lim_{b\to 0} = -12\gamma^2 < 0$ and $\lim_{b\to 1} = 1 > 0$. In addition, we can show that $f'(b) > 0$ when $\gamma \in \left[\underline{\gamma}(\beta), \bar{\gamma}(\beta)\right]$. Therefore, there exist a $\beta_3(\gamma)$ such that $f(b) \leq 0$ (the NSC model leads to a higher total supply chain profit) if and only if $\beta \leq \beta_3(\gamma)$.

- When $\gamma \in [\bar{\gamma}(\beta), 1]$, the technology supplier uses the inclusive strategy in both supply chain models. Comparing the profits we have that the downstream profit and the total supply chain profit are lower in the NSC model, and the technology supplier's profit is higher in the NSC model if and only if

$$-8\beta + 25\beta^2 - 13\beta^3 + (4\beta - 32\beta^2 + 20\beta^3)\gamma + (4 - 4\beta + 12\beta^2 - 8\beta^3)\gamma^2 \leq 0. \tag{A.41}$$

We can show that when $\gamma \geq \bar{\gamma}(\beta)$, condition (A.41) is equivalent to $\beta \leq b_0$ and

$$\gamma \leq \gamma_2(\beta) \equiv \frac{5\beta^3 - 8\beta^2 + (\beta - 2)\sqrt{-\beta\left(\beta^3 - 5\beta^2 + 6\beta - 2\right)} + \beta}{2\left(2\beta^3 - 3\beta^2 + \beta - 1\right)}.$$

Then in this region, the technology supplier's profit is higher in the NSC model if and only if $\bar{\gamma}(\beta) \leq \gamma \leq \gamma_2(\beta)$.

Summarizing all cases and the results follow. □

Proof of Proposition 8. First, we can verify that when $\beta < b_0$ and $\gamma_1(\beta) < \gamma < \gamma_2(\beta)$, if the design license is observable to the manufacturing firm, then the technology supplier's optimal licensing strategy can be interior high royalty separating, boundary high royalty separating, or pooling. The technology supplier is willing to keep the design license confidential, as shown in Proposition 3.

We need to make sure that the design firm also gets more profits by keeping the design license confidential. When $\beta < b_0$ and $\gamma_1(\beta) < \gamma < \gamma_2(\beta)$, it can be shown that if the technology supplier's optimal licensing strategy under observable design license is either interior high royalty separating or boundary high royalty separating, the high-type design firm's profit is always higher under confidential design license; whereas if the technology supplier's optimal licensing strategy under observable design license is pooling, the high-type design firm's profit is higher under confidential design license if

$$\beta\left(\beta(4\beta(\gamma-1)-3\gamma-5)+12\gamma+8\right) \leq 8\gamma. \tag{A.42}$$

Given $\beta \leq 1/2$, which is a condition for pooling to be optimal under observable design licence, equation (A.42) holds if

$$\gamma \geq \frac{\beta\left(4\beta^2+5\beta-8\right)}{4\beta^3-3\beta^2+12\beta-8}. \tag{A.43}$$

Combining the above condition with those in Proposition 7, the results follow. □

PROPOSITION A.1. *Suppose the design license is determined ahead of the manufacturing license and observable to the manufacturer. The technology supplier's optimal licensing strategy is as follows:*

$\beta \leq 1/2$	$\gamma \leq \sqrt{\beta/(3-2\beta)}$: *High-type-only strategy* $\gamma \geq \sqrt{\beta/(3-2\beta)}$: *Pooling strategy*
$\beta \geq 1/2$	$\gamma \leq \frac{\beta+2\sqrt{\beta(1-\beta)^3}}{4-5\beta+2\beta^2}$: *High-type-only strategy* $\frac{\beta+2\sqrt{\beta(1-\beta)^3}}{4-5\beta+2\beta^2} \leq \gamma \leq \beta$: *Separating strategy* $\gamma \geq \beta$: *Pooling strategy*

The optimal royalties are:

- $r_H = 0$ *in the high-type-only strategy;*
- $r_H = 0$ *and* $r_L = \frac{\beta A_H - A_L}{1-\beta}$ *in the separating strategy;*
- $r_H = r_L = 0$ *in the pooling strategy.*

Proof of Proposition A.1. We first derive the technology supplier's optimal high-type-only strategy, then its optimal inclusive strategy, and finally compare the two to derive its eventual optimal strategy.

Under the high-type-only strategy, the technology supplier chooses (r_H, F_H) to maximize

$$\max \beta\left(q_H(r_H)\, r_H + F_H + F_M^H\right)$$
$$\text{s.t. } \pi_H(r_H, F_H) \geq 0 \text{ and } r_H \leq A_H$$

Setting the constraint $\pi_H(r_H, F_H) \geq 0$ binding, we have $\pi_H(r_H, F_H) = (A_H - r_H)^2/16 - F_H = 0$, i.e., $F_H = (A_H - r_H)^2/16$. Substituting $q_H(r_H)$, F_H, and F_M^H into the objective function, we can rewrite the problem as

$$\max \pi_T^H = \beta\left(r_H(A_H - r_H)/4 + (A_H - r_H)^2/16 + (A_H - r_H)^2/8\right)$$
$$\text{s.t. } r_H \leq A_H$$

Since $\partial\pi_T^H/\partial r_H < 0$, it is optimal to set $r_H = 0$. Then $F_H = A_H^2/16$, $F_M^H = A_H^2/8$, and $\pi_T^H = 3\beta A_H^2/16$.

Under the inclusive strategy, the technology supplier's problem can be formulated as follows

$$\begin{aligned}
\max \pi_T^I &= \beta\left(r_H q_H(r_H) + F_H + F_M^H\right) + (1-\beta)\left(r_L q_L(r_L) + F_L + F_M^L\right) \\
&= \beta\left(r_H(A_H - r_H)/4 + F_H + (A_H - r_H)^2/8\right) + \\
&\quad (1-\beta)\left(r_L(A_L - r_L)/4 + F_L + (A_L - r_L)^2/8\right) \\
\text{s.t. IRH} &: \ \pi_H(r_H, F_H) \geq 0 \text{ and } r_H \leq A_H, \\
\text{IRL} &: \ \pi_L(r_L, F_L) \geq 0 \text{ and } r_L \leq A_L, \\
\text{ICH} &: \ \pi_H(r_H, F_H) \geq \pi_H(r_L, F_L), \\
\text{ICL} &: \ \pi_L(r_L, F_L) \geq \pi_L(r_H, F_H) \text{ or } r_H \geq A_L.
\end{aligned}$$

By similar analysis as in the paper, the IRL and ICH constraints are binding, then we have $F_L = (A_L - r_L)^2/16$ and $F_H = \left((A_H - r_H)^2 - (A_H - r_L)^2\right)/16 + (A_L - r_L)^2/16$.

For the ICL constraint $\pi_L(r_L, F_L) \geq \pi_L(r_H, F_H)$, after substituting F_L and F_H into this inequality, we can obtain $r_L \geq r_H$.

To summarize, under inclusive strategy, the technology supplier's problem can be rewritten as

$$\begin{aligned}
\max_{r_H, r_L} \pi_T^I &= \beta(r_H(A_H - r_H)/4 + \left((A_H - r_H)^2 - (A_H - r_L)^2\right)/16 + (A_L - r_L)^2/16 + (A_H - r_H)^2/8) \\
&\quad + (1-\beta)(r_L(A_L - r_L)/4 + (A_L - r_L)^2/16 + (A_L - r_L)^2/8) \\
\text{s.t. } & r_L \leq A_L, \\
& r_H \leq r_L \text{ or } r_H \geq A_L.
\end{aligned}$$

Since $\partial\pi_T^H/\partial r_H = -\beta(A_H + r_H)/8 < 0$, $r_H = 0$. Since $\partial\pi_T^H/\partial r_L = (\beta A_H - A_L - (1-\beta)r_L)/8$, the optimal value for r_L needs to be discussed.

(i) If $\beta A_H \leq A_L$ (i.e., $A_L/A_H \geq \beta$), then $r_L = 0$ which results in pooling strategy. In this case, $\pi_T^I = (A_L^2(3-2\beta) + 2\beta A_H^2)/16$, $\pi_L = 0$, $\pi_H = A_H^2/16 - A_L^2/16$, $F_M^H = A_H^2/8$, and $F_M^L = A_L^2/8$.

(ii) If $\beta A_H \geq A_L$ (i.e., $A_L/A_H \leq \beta$), $r_L = \min\{\frac{\beta A_H - A_L}{1-\beta}, A_L\}$.

(ii.a) When $A_L/A_H \leq \beta/(2-\beta)$, then $\frac{\beta A_H - A_L}{1-\beta} \geq A_L$, and $r_L = A_L$. In this case, $q_L(r_L) = 0$. Therefore, this case is dominated by the high-type-only strategy.

(ii.b) When $A_L/A_H > \beta/(2-\beta)$, $r_L = \frac{\beta A_H - A_L}{1-\beta}$. Then $\pi_T^I = ((4 - 5\beta + 2\beta^2)A_L^2 + \beta(2-\beta)A_H^2 - 2\beta A_H A_L)/(16(1-\beta))$, $\pi_L = 0$, $\pi_H = (A_H - r_L)^2/16 - (A_L - r_L)^2/16$, $F_M^H = A_H^2/8$, and $F_M^L = (A_L - r_L)^2/8$, where $r_L = \frac{\beta A_H - A_L}{1-\beta}$.

Next, compare the technology supplier's profit under the high-type-only strategy and under the inclusive strategy to derive its optimal strategy.

(1) If $A_L/A_H \geq \beta$ (i.e., $\beta A_H \leq A_L$), $\pi_T^I - \pi_T^H = (A_L^2(3-2\beta) - \beta A_H^2)/16$.

(1.a) If $A_L/A_H \geq \sqrt{\beta/(3-2\beta)}$, $\pi_T^I \geq \pi_T^H$. That is, inclusive strategy is optimal for the technology supplier, and $r_H^* = r_L^* = 0$.

(1.b) If $A_L/A_H \leq \sqrt{\beta/(3-2\beta)}$, $\pi_T^I \leq \pi_T^H$. That is, high-type-only strategy is optimal for the technology supplier, and $r_H^* = 0$, $F_H = A_H^2/16$.

(2) If $A_L/A_H \le \beta$ (i.e., $\beta A_H \ge A_L$)

(2.a) If $A_L/A_H \le \beta/(2-\beta)$, by (ii.a) the optimal strategy is high-type-only strategy.

(2.b) If $A_L/A_H \ge \beta/(2-\beta)$, $\pi_T^I - \pi_T^H = \left((4-5\beta+2\beta^2)(A_L/A_H)^2 - 2\beta A_L/A_H - \beta + 2\beta^2\right) A_H^2/(16(1-\beta)) \equiv \Omega A_H^2/(16(1-\beta))$. We can show that Ω is convex in β. $\Omega|_{A_L/A_H=\beta} = \beta(1-\beta)^2(2\beta-1)$ and $\Omega|_{A_L/A_H=\beta/(2-\beta)} = 4\beta(\beta-1)^3/(\beta-2)^2 < 0$.

(2.b1) If $\beta \le 1/2$, $\pi_T^I \le \pi_T^H$ always.

(2.b2) If $\beta > 1/2$, there exists a threshold of A_L/A_H, which equals $\frac{\beta+2\sqrt{\beta(1-\beta)^3}}{4-5\beta+2\beta^2}$, such that $\pi_T^I \le \pi_T^H$ for $A_L/A_H \in [\beta/(2-\beta), \frac{\beta+2\sqrt{\beta(1-\beta)^3}}{4-5\beta+2\beta^2}]$, and $\pi_T^I \ge \pi_T^H$ for $A_L/A_H \in [\frac{\beta+2\sqrt{\beta(1-\beta)^3}}{4-5\beta+2\beta^2}, \beta]$, where $r_H^* = 0$, $r_L^* = \frac{\beta A_H - A_L}{1-\beta}$.

In the following, we summarize the technology supplier's optimal strategy by combining the results above.

First, we note the following equivalences:

$$\beta \le 1/2 \iff \beta \le \sqrt{\beta/(3-2\beta)}$$
$$\beta \le 1/2 \iff \beta \le \frac{\beta+2\sqrt{\beta(1-\beta)^3}}{4-5\beta+2\beta^2}$$

Case 1: $\beta \le 1/2$. This implies $\beta \le \sqrt{\beta/(3-2\beta)}$ and $\beta \le \frac{\beta+2\sqrt{\beta(1-\beta)^3}}{4-5\beta+2\beta^2}$.

Case 1.1: If $A_L/A_H \le \beta$, by (2.b1), $\pi_T^I \le \pi_T^H$. Thus, high-type-only strategy is optimal.

Case 1.2: If $\beta \le A_L/A_H \le \sqrt{\beta/(3-2\beta)}$, by (1.b) $\pi_T^I \le \pi_T^H$. Thus, high-type-only strategy is optimal.

Case 1.3: If $A_L/A_H \ge \sqrt{\beta/(3-2\beta)}$, by (1.a) $\pi_T^I \ge \pi_T^H$. Thus, inclusive strategy is optimal, and $r_H^* = r_L^* = 0$, which is pooling strategy.

Case 2: $\beta \ge 1/2$. This implies $\beta \ge \sqrt{\beta/(3-2\beta)} \ge \frac{\beta+2\sqrt{\beta(1-\beta)^3}}{4-5\beta+2\beta^2} \ge \beta/(2-\beta)$.

Case 2.1: If $A_L/A_H \le \beta/(2-\beta)$, by (2.a) the optimal strategy is high-type-only strategy.

Case 2.2: If $\beta/(2-\beta) \le A_L/A_H \le \frac{\beta+2\sqrt{\beta(1-\beta)^3}}{4-5\beta+2\beta^2}$, by (2.b2) $\pi_T^I \le \pi_T^H$ and hence the optimal strategy is high-type-only strategy.

Case 2.3: If $\frac{\beta+2\sqrt{\beta(1-\beta)^3}}{4-5\beta+2\beta^2} \le A_L/A_H \le \beta$, by (2.b2) $\pi_T^I \ge \pi_T^H$. Thus, the separating strategy with $r_H^* = 0$ and $r_L^* = \frac{\beta A_H - A_L}{1-\beta}$ is optimal.

Case 2.4: If $A_L/A_H \ge \beta$, by (1.a) inclusive strategy is optimal, and $r_H^* = r_L^* = 0$, which is pooling strategy.

□

Proof of the Nonnegative Licensing Fee Extension In the presence of the nonnegative licensing fee constraint, the problem to derive the optimal inclusive strategy under the NSC model with observable design license is written in the extension section 6.3. Note that the IRL and ICH constraints lead to $(A_L-r_L)^2/16 \ge F_L \ge (A_H-r_L)^2/16 - (A_H-r_H)^2/16 + F_H$. Therefore, $F_H \le (A_L-r_L)^2/16 - (A_H-r_L)^2/16 + (A_H-r_H)^2/16$. If the ICL constraint is satisfied by $r_H \ge A_L$, then $(A_H-r_H)^2/16 \le (A_H-A_L)^2/16$ and $F_H \le (A_L-r_L)^2/16 - (A_H-r_L)^2/16 + (A_H-A_L)^2/16 = (A_L-A_H)(A_L+A_H-2r_L)/16 + (A_H-A_L)^2/16 = (A_L-A_H)(A_L + A_H - 2r_L + A_L - A_H)/16 = (A_L-A_H)(2A_L-2r_L) \le 0$. This, together with the constraint of $F_H \ge 0$, leads to $F_H = 0$. As a result, the IRL and ICH constraints lead to $(A_L-r_L)^2/16 \ge F_L \ge (A_H-r_L)^2/16 - (A_H-r_H)^2/16$. By $r_H \ge A_L$, we have $(A_L-r_L)^2/16 \ge F_L \ge (A_H-r_L)^2/16 - (A_H-A_L)^2/16 = (A_L-r_L)(2A_H-r_L-A_L)/16$. If $A_L > r_L$, then $(A_L - r_L)/16 \geq (2A_H - r_L - A_L)/16$, which is equivalent to $A_L \geq A_H$, contradicting the assumption of $A_L < A_H$. Therefore, it is only possible that $A_L = r_L$. By the IRL constraint and $F_L \geq 0$, we have $F_L = 0$. By the ICH constraint and $r_H \geq A_L$, we have $r_H = A_L$.

To summarize, if the ICL constraint is satisfied by $r_H \geq A_L$, then we have $r_H = r_L = A_L$, and $F_L = F_H = 0$. In this case, the low-type design firm's selling quantity is zero and the technology supplier gets zero profit from the low type. Then the inclusive strategy is dominated by the high-type-only strategy. Therefore, the ICL constraint satisfied by $r_H \geq A_L$ can never be optimal for the technology supplier.

The other way to satisfy the ICL constraint is through $\pi_L^o(r_L, F_L) \geq \pi_L^o(r_H, F_H)$. Standard analysis tells that the IRL and ICH constraints are binding. That is, $F_L = (A_L - r_L)^2/16$ and $F_H = (A_H - r_H)^2/16 - (A_H - r_L)^2/16 + F_L$. Then $\pi_L^o(r_L, F_L) \geq \pi_L^o(r_H, F_H)$ leads to $r_H \leq r_L$. Under these conditions, $F_H, F_L \geq 0$ are satisfied. Substituting the expressions of F_H and F_L into the objective function, we derive the objective function as a jointly concave function in r_H and r_L. First order condition leads to the same r_L^{OS} and r_H^{OS} as in Lemma A.1. In the proof of Lemma A.1., there are 6 cases. By adding the constraint of $F_H, F_L \geq 0$, only Case 1.1 and Case 2.1 need to be re-analyzed. In Case 1.1, $r_L^{OS} < A_L$, but $r_H^{OS} = A_H/3 > A_L > r_L^{OS}$, which violates the constraint of $r_H \leq r_L$. By the joint concavity of the objective function in r_H, r_L, optimally, (r_H, r_L) should move to the pooling boundary. Therefore, in Case 1.1, pooling strategy is the optimal inclusive strategy. Similarly, in Case 2.1, the first-order solution (r_H^{OS}, r_L^{OS}) falls in the infeasible region. Again, by the joint concavity of the objective function in r_H, r_L, (r_H, r_L) should move to the pooling boundary in the optimal inclusive strategy. Therefore, pooling is the optimal inclusive strategy for both Case 1.1 and Case 2.1, which correspond to Regions 2,4,5 in Figure 3(a). By comparing the technology supplier's profit under the pooling strategy with that under the high-type-only strategy, we can derive its final optimal strategy. As a clear illustration, the technology supplier's optimal strategy under the NSC model with observable design license and nonnegative licensing fee is summarized in Figure 8, with the solid lines separating the three regions of optimal policy: High type only, interior low-royalty separating, and pooling. For the downstream firm's profit comparison between the integrated model and the NSC model with observable design license and constraint of $F_H, F_L \geq 0$, we have the following profit expressions.

Under the NSC model with observable design license and nonnegative licensing fee:

When low-royalty separating strategy is used,

$$\pi_H^{OS} = \frac{(A_H - A_L)(5A_H\beta - 3A_H - A_L\beta - A_L)}{48(\beta - 1)}.$$

When pooling strategy is used,

$$\pi_H^{OP} = \frac{(A_H - A_L)(A_L(4\beta + 1) - A_H(4\beta - 3))}{48}.$$

When high-type-only strategy is used,

$$\pi_H^{OH} = 0.$$

Under the integrated model:

When separating strategy is used,

$$\pi_H^{IS} = \frac{(A_H - A_L)(3A_H\beta - A_H - A_L\beta - A_L)}{4(\beta - 1)}.$$

When high-type-only strategy is used,

$$\pi_H^{IH} = 0.$$

The comparison results are summarized in the extension section. $\square$