

The Impact of Contracts and Competition on Upstream Innovation in a Supply Chain

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January 2014

Abstract

We consider a supply chain with an upstream supplier who invests in innovation and a downstream manufacturer who sells to consumers. We study the impact of supply chain contracts with endogenous upstream innovation, focusing on three different contract scenarios: (i) a wholesale price contract, (ii) a quality-dependent wholesale price contract, and (iii) a revenue-sharing contract. We confirm that the revenue-sharing contract can coordinate supply chain decisions including the innovation investment, whereas the other two contracts may result in underinvestment in innovation. However, the downstream manufacturer does not always prefer the revenue-sharing contract; the manufacturer's profit can be higher with a quality-dependent wholesale price contract than with a revenue-sharing contract, specifically when the upstream supplier's innovation cost is low. We then extend our model to incorporate upstream competition between suppliers. By inviting upstream competition, with the wholesale price contract, the manufacturer can increase his profit substantially. Furthermore, under upstream competition, the revenue-sharing contract coordinates the supply chain, and results in an optimal contract form for the manufacturer when suppliers are symmetric. We also analyze the case of complementary components suppliers, and show that most of our results are robust.

Keywords: supply chain management; innovation; quality; contracts; competition

Received: December 2010; accepted: December 2013 by Mark Ferguson, Glen Schmidt, and Gil Souza after five revisions.

1 Introduction

Innovation is one of the key drivers in the creation of high-technology products such as iPad. These days, firms rely less on internal resources that they control directly, but instead, more companies are purchasing components from suppliers who drive innovation to enhance the product quality.¹ For example, the technology giant Apple procures components such as displays and CPUs from its suppliers, whose innovation significantly affects the performance of Apple's products such as the iPad (Apple 2013a). Recently, Apple's relationship with Samsung has been deteriorating, and as a result, Samsung is not supplying displays for the new iPad Mini. This implies that Apple currently has one display supplier, LGD, who has been Apple's supplier previously and one new untested supplier, AUO (Cohan 2012). It is important for Apple to motivate LGD and AUO to innovate in display technologies. Based on Bob Ferrari, a supply chain technology executive, one significant challenge for Apple's supply chain is whether it can successfully foster the required new innovations in the display technologies of its display suppliers (Ferrari 2012). Thus, it is important for managers of manufacturers such as Apple to understand the key drivers and incentives of innovation by suppliers such as LGD in supply chain settings.

Understanding the importance of upstream innovation, what can a manufacturer do to motivate the upstream suppliers to invest more in innovation (which improves the product quality and thus increases consumers' willingness to pay for products) and increase his profits?² In addition, how can a manufacturer gain more profits from the supplier's higher innovation investment? First, the manufacturer may consider alternative supply chain contracts, which leads to our first research question: Which contract form is most effective in motivating the upstream supplier to innovate, and which contract form helps maximize the manufacturer's profit? Second, the manufacturer

¹In the remainder of the paper, we refer to the downstream firm as the *manufacturer* and the upstream innovating firm as the *supplier*. However, our analysis also applies to the upstream manufacturer and downstream retailer setting.

²We designate the upstream supplier(s) as *female* and the downstream manufacturer as *male*.

may invite competition between upstream suppliers to incentivize them to invest in innovation. Correspondingly, our second research question focuses on the impact of upstream competition on the upstream suppliers' incentives to innovate, and, in turn, on the manufacturer's profit. Third, for products such as iPad, there exists a strong complementarity between components, for example, between hardware and software (Cheng 2012). In this case, what is the impact of complementarity on upstream innovation and the profits of firms within a supply chain? The second and third questions may help managers of manufacturers to better understand the impact of the supply chain structure on innovation and profits.

In this paper, we consider a supply chain with a manufacturer and an upstream supplier. The supplier invests in innovation, that increases the value of the product to consumers, and the manufacturer sets the product price and sells to consumers. We study the impact of different contracts on innovation by focusing on three types of contracts: *(i)* the wholesale price contract, *(ii)* the quality-dependent wholesale price contract, and *(iii)* the revenue-sharing contract. We find that with endogenous supplier innovation, the revenue-sharing contract can always coordinate the supply chain, i.e., achieve the supply chain optimal innovation level and product price, whereas the other two contracts fail to coordinate the supply chain, performing especially bad, when the innovation cost is high. From the manufacturer's point of view, however, the revenue-sharing contract does not always maximize his profit. Specifically, the revenue-sharing contract is the manufacturers best choice (i.e, it maximizes the manufacturers profit) when innovation is relatively expensive, and in this case the other two contracts we analyze fail to effectively incentivize innovation. In contrast, when the innovation cost is low, the quality-dependent wholesale price contract maximizes the manufacturers profit and in this case, like the revenue-sharing contract, it coordinates the supply chain. Thus, from the manufacturers perspective, the quality-dependent wholesale price contract is preferred when innovation cost is low (it dominates the wholesale price contract because with the

wholesale price contract, the supplier chooses both the wholesale price and the quality, whereas in the quality-dependent wholesale price contract, the manufacturer effectively makes all the supply chain decisions).

Examining the impact of upstream competition between suppliers, we show that with the wholesale price contract, inviting upstream competition can significantly increase the manufacturer's profit. Furthermore, if the two competing suppliers are symmetric, both the wholesale price contract and the quality-dependent wholesale price contract result in the same supply chain decisions and profits, which are also the same as those under upstream monopoly with the quality-dependent wholesale price contract. The revenue-sharing contract not only coordinates the supply chain, but also maximizes the manufacturer's profit if the two competing suppliers are symmetric. Finally, we extend our model to analyze complementary suppliers.

Our paper makes two contributions to the literature: First, we contribute to the supply chain contracting literature by incorporating the endogenous upstream innovation decision. We specifically demonstrate how supply chain contracts can coordinate the supply chain in achieving the optimal suppliers' innovation in addition to the optimal production volume and pricing; we compare the effects of widely used contracts in motivating the upstream supplier to invest in innovation, as well as the impact of those contract types on the manufacturer's profit. The existing supply chain contracting literature has primarily focused on the production volume and pricing aspects of coordination, whereas this paper extends this literature by including the upstream innovation.³

Second, we analyze the impact of upstream competition with these contracts. Our result implies that inviting upstream competition can serve as a substitute for the power to choose the contract form from the manufacturer's point of view, which provides an additional reason for managers of manufacturers to have competing suppliers rather than an exclusive one, especially when simple

³We are thankful to the Senior Editor and the reviewers for suggesting this positioning of our paper.

wholesale price contracts are used in the supply chain.

The remainder of the paper is organized as follows: Section 2 reviews the related literature. Section 3 introduces the model and analyzes the three distinct contracts. By comparing the performances of different contracts, we provide our key insights and the answers to our research questions in Section 4. Section 5 extends the model to include upstream competition for both substitutes and complements. Section 6 offers concluding remarks. All proofs are in the Appendix.

2 Literature Review

Our paper is broadly related to two streams of literature: The first is the literature on supply chain contracting and coordination and specifically the works that study coordinating product quality decisions in supply chains and supply chain coordination problems with endogenous innovation; the second is the literature in operations management on innovation and new product development.

In the supply chain contracting and coordination literature, Jeuland and Shugan (1983) discuss the problems in channel coordination as well as the mechanisms attempting to coordinate the channel, and derive the form of the quantity-discount schedule that leads to optimum channel profits. Lal and Staelin (1984) discuss how and why a supplier should offer a discount-pricing structure, even if it does not alter the ultimate demand. Cachon (2003) provides an extensive review of the existing supply chain contracting literature. Cachon and Lariviere (2005) explore the merits and limitations of the revenue-sharing contract. Wang et al. (2004) show that under a consignment contract with revenue-sharing, the overall channel profit and the retailer's profit depend on the demand price elasticity and on the retailer's share of channel costs. Ozer and Raz (2011) analyze a supply chain structure with two competing suppliers and one manufacturer, focusing on asymmetric information. Comparing to the exogenous product quality assumed in these papers, we endogenize the product quality decision and analyze which contract form can

coordinate supply chain decisions, including the supplier's innovation investment, which determines the product quality. Some previous works studying coordination of product quality decisions in supply chains focus on product-line decisions. By examining how selling through a retailer affects an upstream manufacturer's product-line decision compared to direct selling, Villas-Boas (1998) shows that when selling through a retailer, the manufacturer should increase the quality differences of the products. Liu and Cui (2010) examine how a manufacturer designs the product line in centralized versus decentralized channels, and find that the product-line decision can be socially optimal in a decentralized channel, whereas it is never socially optimal in a centralized channel. These two papers focus on product quality decisions from a product-line perspective, i.e., how to decide qualities of multiple products, without explicitly considering the fundamental action that improves product quality, i.e., the innovation investment. Our paper extends the supply chain contracting literature by analyzing the impact of different contracts on supplier's investment in innovations, which has been underexplored in this literature.

Focusing on the supply chain coordination problem with endogenous downstream innovation, Gilbert and Cvsa (2003) examine mechanisms that stimulate downstream innovation in a supply chain. They analyze the effect of price commitment by the upstream supplier. Adelman et al. (2014) take the upstream firm's point of view. They address the question of when and how an upstream firm can encourage its customers to improve their products and charge customers a premium. Different from these two papers, we study the innovation investment decision by the upstream supplier, instead of the downstream agents. Several other papers also incorporate upstream innovation. Gupta and Loulou (1998) analyze the manufacturers' incentive in process innovation when selling through downstream retailers. Yao et al. (2011) use a principal-agent model to study the downstream buyers' problem in inducing suppliers to adopt new technologies, focusing on unobservable adoption costs and investment. Zhu et al. (2007) study a buyer's effort in pushing

investment in the quality control process of its supplier. However, the types of innovation considered in these papers are different from that in ours, which is the supplier's product innovation that increases the value of the product to consumers. Bhaskaran and Krishnan (2009) examine revenue sharing, investment (cost) sharing and innovation (effort) sharing contracts in collaborating new product development, and show that for projects with substantial timing uncertainty, investment sharing works better, whereas for projects with quality uncertainty, innovation sharing tends to be more attractive under certain conditions. They focus on innovation collaboration, whereas we study the case where the supplier invests in innovation to improve the product quality. Studying firm's decision on whether to outsource manufacturing (process innovation) or both manufacturing and design (product innovation), Druehl and Raz (2013) demonstrate that a firm never outsources both manufacturing and design under a wholesale price contract. However, the firm may outsource both when it employs a two-part tariff contract. Compared to their analysis on the decisions to outsource process and product innovation, we focus on different contracts, i.e., a revenue sharing contract, in motivating upstream (product) innovation.

The literature in operations management on innovation and new product development was reviewed extensively in Krishnan and Ulrich (2001); most of the papers in this literature focus on product innovation and development within a single firm. Ulku et al. (2005) turn their attention to supply chain issues, by investigating the timing of process adoption for new products, and demonstrate that outsourced manufacturing can hurt the original equipment manufacturer (OEM), in which case the OEM can share the risk through joint investment to accelerate the process adoption. In contrast to these and many other papers in this literature, we study a supply chain set-up and focus on the impact of supply chain contracts on an upstream supplier's innovation as well as the manufacturer's profit.

3 Model

In this section, we consider a baseline supply chain structure with one upstream supplier who invests in innovation and sells through a manufacturer. We utilize the horizontal product differentiation model (i.e., Hotelling 1929); specifically, consumers are uniformly distributed on a unit interval $[0, 1]$ and the manufacturer owns one store located in the middle. Consumers have a per-unit traveling cost t . A consumer's utility is the product quality less her traveling cost and the product price. For example, if a consumer located at $x \in [0, 1]$ buys a product with quality Q at price p from the manufacturer, her net utility is $u = Q - p - |x - \frac{1}{2}|t$. A consumer needs at most one product and makes her purchase decision to maximize her net utility.

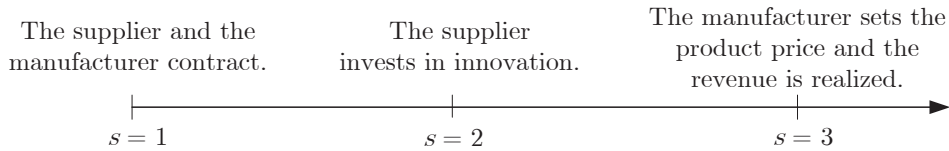


Figure 1: The model timeline

The timeline of our model is illustrated in Figure 1. There are three stages. In the initial stage, $s = 1$, the supplier and the manufacturer sign the contract. We consider three different contracts: (i) the supplier sets the wholesale price w and makes a take-it-or-leave-it offer to the manufacturer; (ii) the manufacturer establishes a menu of wholesale prices, depending on the quality of the product, and makes a take-it-or-leave-it offer to the supplier; and (iii) the two parties employ a revenue-sharing contract in which the manufacturer first offers to share “ a ” portion of its revenue to the supplier, then the supplier decides on the wholesale price w .⁴ The supplier also has a nonnegative reservation profit $R \geq 0$, which means, the supplier will not participate if her profit is lower than R .⁵ In the second stage, $s = 2$, the supplier makes an innovation investment, which determines

⁴If the supplier sets both the revenue share and the wholesale price, she can set a negative wholesale price equal (in absolute terms) to the manufacturer's unit manufacturing cost (reimburse the manufacturer his manufacturing cost) and ask for almost all of the revenue. By doing so, the supply chain is immediately coordinated, and the supplier is able to obtain the optimal supply chain profit.

⁵This is a standard approach to model bargaining power (Cachon 2003). R can also be interpreted as the supplier's

the product quality Q , and incurs the corresponding investment cost $CQ^2/2$. The unit production cost c_S for the supplier is increasing with this quality Q ; specifically, $c_S = kQ$ with $k > 0$. Finally, in the last stage, $s = 3$, the manufacturer sets the product price and revenues are realized. The manufacturer also has a unit manufacturing cost c_M , and a reservation profit (Bernstein and Marx 2010; Lariviere and Padmanabhan 1997; Desai 2000), which we denote as R_M . We assume that the manufacturer's reservation profit is not too large, that is, $R_M \leq t/2$.⁶

We analyze the centralized supply chain, i.e., the first-best case, and the three distinct contracts in Sections 3.1 to 3.4 respectively. We provide the complete equilibrium outcome expressions for those cases in Proposition 1 in Section 4.

3.1 The Centralized Supply Chain

We first consider a centralized supply chain in which the pricing and innovation decisions are jointly made by a central planner, to maximize the total supply chain profit. This is the first-best case, and the total supply chain profit is maximized. In order for the results to be comparable to decentralized supply chains, we assume that the centralized supply chain also has a reservation profit $R + R_M$, and it will invest in innovation only if it expects to make a profit no less than $R + R_M$. We begin by analyzing consumers' choices. In stage 3, given innovation level Q , if the central planner charges a product price $p > Q - t/2$, the consumers located at both ends (0 and 1) get utility $Q - t/2 - p < 0$ by purchasing, so the market is partially covered, that is, only a fraction of consumers buy the product, and the total demand is $2(Q - p)/t$. However, if the central planner charges a price $p \leq Q - t/2$, all customers obtain nonnegative utility by purchasing, so the market is fully covered, that is, all consumers purchase the product. Therefore, the total supply chain profit

fixed innovation and manufacturing costs. The profits will be different under this alternative interpretation, but all our primary results still hold.

⁶If the manufacturer's reservation profit is higher than the first-best profit less the supplier's reservation profit, then no transaction occurs, as expected. In the intermediate range, the expressions for equilibrium outcomes presented in Proposition 1 and Tables 1 will be different and some regions will not exist. However, our main insights remain valid.

can be written as:

$$\pi_{SC}(Q, p) = \begin{cases} p - kQ - c_M - \frac{CQ^2}{2}, & \text{if } p \leq Q - \frac{t}{2}; \\ \frac{2(Q-p)(p-kQ-c_M)}{t} - \frac{CQ^2}{2}, & \text{if } Q - \frac{t}{2} < p \leq Q; \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

Solving this profit-maximization problem $\max_{p,Q} \pi_{SC}(p, Q)$ and comparing the maximized supply chain profit with the total reservation profit $R+R_M$, we obtain the first-best benchmark supply chain decisions and profit in the centralized supply chain. We next analyze the decentralized supply chains with three different types of contracts. We say that a contract coordinates the supply chain if the equilibrium decisions under the contract are the same as the first-best benchmark supply chain decisions.

3.2 The Wholesale Price Contract

The wholesale price contract is widely used in many supply chain settings (Lariviere and Porteus 2001). To obtain the supply chain decisions and profits in equilibrium, we solve by backwards induction. In stage 3, given the innovation level Q and the product price p , the consumer's problem is the same as that in the benchmark case. Considering the wholesale price w and consumers' decisions, we can write the manufacturer's pricing problem in stage 3 as follows:

$$\pi_M(p) = \begin{cases} p - w - c_M, & \text{if } p \leq Q - \frac{t}{2}; \\ \frac{2(Q-p)(p-w-c_M)}{t}, & \text{if } Q - \frac{t}{2} < p \leq Q; \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

Optimizing (2) over p , we obtain the optimal product price:

$$p^*(w) = \begin{cases} Q - \frac{t}{2}, & \text{if } w \leq Q - t - c_M; \\ \frac{Q+w+c_M}{2}, & \text{otherwise.} \end{cases} \quad (3)$$

Note that if $w > Q - c_M$, then the manufacturer cannot sell products profitably and will choose not to participate (setting $p^*(w) \geq Q$ generates no demand). Anticipating that the manufacturer will set the product price as in (3), the supplier's corresponding profit in terms of the wholesale price and innovation level is

$$\pi_S(w, Q) = \begin{cases} w - kQ - \frac{CQ^2}{2}, & \text{if } w \leq Q - t - c_M; \\ \frac{(Q-w-c_M)(w-kQ)}{t} - \frac{CQ^2}{2}, & \text{if } Q - t - c_M < w \leq Q - c_M; \\ -\frac{CQ^2}{2}, & \text{otherwise.} \end{cases} \quad (4)$$

The supplier then sets the wholesale price w and the innovation level Q to maximize her profit in (4). After optimizing over the wholesale price w and the innovation level Q , and comparing firms' optimal profits with their respective reservation profits, we obtain the supply chain decisions and profits in equilibrium.

3.3 The Quality-dependent Wholesale Price Contract

In some industries, the manufacturer may have specific requirements regarding the quality of the component and commit to buying components that satisfy these requirements at a wholesale price. For example, in buying displays for iPad 3, Apple defines a Retina Display to satisfy that "pixel density is so high your eye is unable to distinguish individual pixels" (Crothers 2011). LG and Sharp failed to supply displays for iPad 3, because they could not meet Apple's quality requirements (Yang 2012). With a quality-dependent wholesale price contract, the manufacturer first offers the supplier

a menu of wholesale prices $w(Q)$ in stage 1. After observing this menu of prices, the supplier invests in innovation, which leads to a product quality Q^* in stage 2. Finally, the manufacturer determines the product price, and revenues are realized in stage 3. In order to obtain the equilibrium supply chain decisions and profits under this contract, we start analyzing backwards from stage 3; in this stage, given fixed w and Q , the manufacturer optimally sets the price p in order to maximize his profit, which is the same as that in the wholesale price contract case, as given in equation (2). The optimal product price is the same as that in equation (3).

By plugging (3) into (2), the manufacturer's corresponding profit as a function of Q and w becomes

$$\pi_M(w, Q) = \begin{cases} Q - \frac{t}{2} - w - c_M, & \text{if } w \leq Q - t - c_M; \\ \frac{(Q-w-c_M)^2}{2t}, & \text{if } Q - t - c_M < w \leq Q - c_M; \\ 0, & \text{otherwise.} \end{cases} \quad (5)$$

The supplier's profit in this case as a function of w and Q is:

$$\pi_S(w; Q) = \begin{cases} w - kQ - \frac{CQ^2}{2}, & \text{if } w \leq Q - t - c_M; \\ \frac{(Q-w-c_M)(w-kQ)}{t} - \frac{CQ^2}{2}, & \text{if } Q - t - c_M < w \leq Q - c_M; \\ 0, & \text{otherwise.} \end{cases} \quad (6)$$

Even though the manufacturer offers a menu of wholesale prices, he is effectively choosing a desired quality Q^* and a corresponding wholesale price w^* , since the manufacturer can offer a zero wholesale price for all other qualities to minimize the incentive for the supplier to deviate from Q^* . Consequently, the manufacturer's problem becomes what to choose for Q and w in order to maximize his own profit (5) subject to the constraint that the supplier's profit (6) is no less than her own reservation profit R . Moreover, this constraint should be binding, since otherwise the manu-

facturer can always offer a lower wholesale price w and increase his profit. Solving this constrained optimization problem, and comparing the manufacturer's optimal profit with his reservation profit R_M , we obtain the supply chain decisions and profits in equilibrium.

3.4 The Revenue-sharing Contract

In the supply chain contracting literature focusing on production quantities and prices, the revenue-sharing contract is usually considered to be a contract that can coordinate the supply chain (Cachon and Lariviere 2005). The revenue-sharing contract is also used in some industries: For example, the movie rental industry has been using revenue-sharing contracts for years (Narayanan and Brem 2003; Girotra et al. 2010). Apple also uses revenue-sharing contracts and shares 70% of the sale revenue with its app developers, whose products significantly increase the value of Apple's products such as iPad and iPhone (Apple 2013b). In this section, we analyze the revenue-sharing contract with endogenous upstream innovation and examine whether it can coordinate the supply chain in such a setting.

From the manufacturer's point of view, it is plausible to implement the revenue-sharing contract before the supplier invests in innovation to encourage the supplier to invest more in innovation; specifically, in this contract, the manufacturer first sets a , the fraction of his revenue that he will share with the supplier (stage $s = 1$). As a increases, the supplier obtains more revenue share, which then provides her with an incentive to invest more in innovation. After observing this fraction a , the supplier invests in innovation, and sets a wholesale price w (stage $s = 2$). Finally, the manufacturer sets the product price and revenues are realized (stage $s = 3$).

To obtain the supply chain decisions and profits in equilibrium, we solve this game backwards, starting from stage 3, in which the manufacturer sets the product price, given the wholesale price w , the innovation level Q , and the supplier's revenue share a . The manufacturer's profit as a function

of the price p can be written as:

$$\pi_M(p; w, Q, a) = \begin{cases} (1-a)p - w - c_M, & \text{if } p \leq Q - \frac{t}{2}; \\ \frac{2(Q-p)((1-a)p - w - c_M)}{t}, & \text{if } Q - \frac{t}{2} < p \leq Q; \\ 0, & \text{otherwise.} \end{cases} \quad (7)$$

Optimizing over p , we obtain the optimal product price:

$$p^*(w, Q, a) = \begin{cases} Q - \frac{t}{2}, & \text{if } w \leq (Q-t)(1-a) - c_M; \\ \frac{Q(1-a) + w + c_M}{2(1-a)}, & \text{otherwise.} \end{cases} \quad (8)$$

The market is fully covered if $w \leq (Q-t)(1-a) - c_M$, whereas if $(Q-t)(1-a) - c_M < w \leq (1-a)Q - c_M$, the market is partially covered, in which case the consumer demand is $\frac{Q(1-a) - w - c_M}{t(1-a)}$. If $w > (1-a)Q - c_M$, then $p^*(w, Q, a) > Q$ and there is no demand. In stage 2, anticipating that the manufacturer will set his price p optimally as in (8), the supplier determines the optimal Q and w to maximize her own profit, which is

$$\pi_S(w, Q; a) = \begin{cases} (a-k)Q - \frac{CQ^2}{2} - \frac{at}{2} + w, & \text{if } w \leq (Q-t)(1-a) - c_M; \\ \frac{(Q(1-a) - w - c_M)((1-a)(a-2k)Q + (2-a)w + ac_M)}{2(1-a)^2t} - \frac{CQ^2}{2}, & \text{if } (Q-t)(1-a) - c_M < w \\ & \leq (1-a)Q - c_M; \\ -\frac{CQ^2}{2}, & \text{otherwise.} \end{cases} \quad (9)$$

By optimizing (9) over w and Q , and comparing the optimized supplier's profit with her reservation

profit R , it follows that

$$(Q^*(a), w^*(a)) = \begin{cases} (0, 0), & \text{if } a < 2 - \frac{(1-k)^2}{Ct} + \frac{2(c_M+R)}{t}; \\ \left(\frac{1-k}{C}, \left(\frac{1-k}{C} - t\right)(1-a) - c_M\right), & \text{otherwise.} \end{cases} \quad (10)$$

Finally, in stage 1, taking (10) into consideration, to maximize his profit, the manufacturer determines the optimal revenue share a for the supplier, which can be written as:

$$\pi_M(a) = \begin{cases} 0, & \text{if } a < 2 - \frac{(1-k)^2}{Ct} + \frac{2(c_M+R)}{t}; \\ \frac{t(1-a)}{2}, & \text{otherwise.} \end{cases} \quad (11)$$

Then, the manufacturer's optimal a becomes

- (i) if $\frac{(1-k)^2}{Ct} - \frac{2(c_M+R)}{t} < 1$, then $Q^* = 0$, and no revenue to share; hence, a does not matter;
- (ii) if $1 \leq \frac{(1-k)^2}{Ct} - \frac{2(c_M+R)}{t} \leq 2$, then the optimal a is $2 - \frac{(1-k)^2}{Ct} + \frac{2(c_M+R)}{t}$, and the corresponding manufacturer's profit is $\frac{(1-k)^2}{2C} - c_M - R - \frac{t}{2}$, which is no smaller than the manufacturer's reservation profit R_M if and only if $C \leq \frac{(1-k)^2}{t+2(c_M+R+R_M)}$. Therefore, $a^* = 2 - \frac{(1-k)^2}{Ct} + \frac{2(c_M+R)}{t}$ and $Q^* = \frac{1-k}{C}$ when $\frac{(1-k)^2}{2(t+c_M+R)} \leq C < \frac{(1-k)^2}{t+2(c_M+R+R_M)}$, and no innovation occurs in equilibrium otherwise;
- (iii) if $\frac{(1-k)^2}{Ct} - \frac{2(c_M+R)}{t} > 2$, then $a^* = 0$, $Q^* = \frac{1-k}{C}$, and $\pi_M^* = \frac{t}{2} \geq R_M$.

Consequently, the wholesale price and profits in equilibrium are obtained by plugging the revenue share a and the innovation level Q back to equations (9), (10), and (11).

4 The Impact of the Different Contracts on Innovation and Profits

We have studied the centralized supply chain and the three different supply chain contracts. The following proposition summarizes and presents equilibrium supply chain decisions and profits.

Proposition 1 *The supply chain decisions and firms' profits under the three different contracts are presented in Table 1.*

When the supplier sets the wholesale price, the manufacturer still has the right to set the product price. Therefore, the supplier cannot reap all of the supply chain profit. Comparing the innovation level with that of the centralized supply chain, we can see that when the innovation cost is low, i.e., $C \leq \frac{(1-k)^2}{2(t+c_M+R)}$, the supply chain optimal innovation level is achieved, because when the product quality is high, the manufacturer obtains a constant profit $t/2$, while the supplier enjoys all the additional benefit of improving the product quality. In other words, the supplier reaps all of the marginal benefit of innovation and is willing to innovate up to the first-best level. In this region, the market is always fully covered in equilibrium; therefore, even though both the supplier and the manufacturer add margins on top of their respective unit costs, the demand is still fixed and the optimal total supply chain profit can still be achieved. Furthermore, the supplier sets the wholesale price in such a way that the manufacturer barely wants to sell to all consumers. That is, if the supplier increases her wholesale price by a little, then the manufacturer will increase the product price and only not all consumers will buy the product. However, when innovation is relatively costly, i.e., $C > \frac{(1-k)^2}{2(t+c_M+R)}$, the total supply chain profit is lower. After giving the manufacturer his profit, innovation becomes unprofitable for the supplier; thus, she does not innovate. In this case, the wholesale price contract does not coordinate the supply chain.

Parameter range	The revenue-sharing contract	The wholesale price contract	The quality-dependent wholesale price contract
$C \leq \frac{(1-k)^2}{2(t+c_M+R)}$	$Q^* = \frac{1-k}{C}, p^* = \frac{1-k}{C} - \frac{t}{2}, a^* = 0$, and $\pi_{sc} = \frac{(1-k)^2}{2C} - c_M - \frac{t}{2}$ $w^* = \frac{1-k}{C} - t - c_M$ $\pi_M = \frac{t}{2}$ $\pi_S = \frac{(1-k)^2}{2C} - c_M - t$		$w^* = \frac{1-k^2}{2C} + R$ $\pi_M = \frac{(1-k)^2}{2C} - c_M - R - \frac{t}{2}$ $\pi_S = R$
$\frac{(1-k)^2}{2(t+c_M+R)} < C \leq \frac{(1-k)^2}{t+2(c_M+R+R_M)}$	$Q^* = \frac{1-k}{C}, p^* = \frac{1-k}{C} - \frac{t}{2}$ $\pi_{sc} = \frac{(1-k)^2}{2C} - c_M - \frac{t}{2}$ $a^* = 2 - \frac{(1-k)^2}{Ct} + \frac{2(c_M+R)}{t}$ $w^* = \frac{(1-k^2)(1-k)}{C^2t} - \frac{(1-k)(2c_M+2R+kt)}{Ct} + c_M + 2R - t$ $\pi_M = \frac{(1-k)^2}{2C} - c_M - R - \frac{t}{2}, \pi_S = R$	No innovation	
$C > \frac{(1-k)^2}{t+2(c_M+R+R_M)}$	No innovation		

Table 1: The supply chain decisions and firms' profits under the three different contracts. The centralized supply chain has the same innovation level, product price, and the total supply chain profits as the revenue-sharing case.

In the quality-dependent wholesale price contract, all the supply chain decisions, i.e., the quality level, the wholesale price and the product price, are effectively made by one party, the manufacturer. As a result, at a first glance, one may expect the quality-dependent wholesale price contract to coordinate the supply chain and maximize the total supply chain profit. However, comparing the equilibrium product quality with that in the first-best case, we see that this quality-dependent wholesale price contract does not always coordinate the supply chain, despite the fact that the manufacturer effectively makes all the supply chain decisions. This is because the manufacturer can only reimburse the innovation cost to the supplier through a wholesale price rather than a lump sum transfer. As a result, the manufacturer has to set the wholesale price above the supplier's marginal production cost, and thus, in the last stage when the manufacturer sets the product price, the double marginalization problem remains. In other words, because the product price is set after firms sign the contract, the manufacturer cannot commit to a fixed consumer product price (and thus commit to a fixed quantity sold) upfront to solve the problem of double marginalization.

In contrast, the revenue-sharing contract always coordinates the supply chain. When the innovation cost is relatively low $\left(C \leq \frac{(1-k)^2}{2(t+c_M+R)}\right)$, the supplier has enough incentive to innovate by merely generating revenue through the wholesale price. The manufacturer does not need to provide additional incentives to the supplier by sharing his revenue. In this case, the supply chain decisions and profits in equilibrium are the same as those when the supplier sets the wholesale price. When the innovation cost is intermediate $\left(\frac{(1-k)^2}{2(t+c_M+R)} < C \leq \frac{(1-k)^2}{t+2(c_M+R+R_M)}\right)$, if the manufacturer does not share any revenue with the supplier, i.e., $a = 0$, then the supplier does not want to innovate. As a result, in order to provide an incentive for the supplier to innovate, the manufacturer gives a positive portion of his revenue to the supplier. However, the manufacturer shares the minimum portion needed and the supplier gets her reservation profit R . Finally, when innovation is so expensive that even in the first-best centralized case, the supply chain profit cannot

be positive $\left(C > \frac{(1-k)^2}{t+2(c_M+R+R_M)}\right)$, there is no innovation in a decentralized supply chain with the revenue-sharing contract either.

It is also worth noting that there is a range of a over which the supply chain is coordinated. Specifically, comparing the innovation level in equation (10) with the supply chain optimal one as shown in Table 1, we find the range of the revenue share under which the supply chain is coordinated, as presented in the following corollary:

Corollary 1 *With the revenue-sharing contract,*

(i) *when $C \leq \frac{(1-k)^2}{2(t+c_M+R)}$, then for all $a \in [0, 1]$, the supply chain is coordinated;*

(ii) *when $\frac{(1-k)^2}{2(t+c_M+R)} < C \leq \frac{(1-k)^2}{t+2(c_M+R+R_M)}$, then the supply chain is coordinated for $2 - \frac{(1-k)^2}{Ct} + \frac{2(c_M+R)}{t} \leq a \leq 1$;*

(iii) *when $\frac{(1-k)^2}{t+2(c_M+R+R_M)} < C \leq \frac{(1-k)^2}{t+2(c_M+R)}$, then the supply chain is coordinated for $0 \leq a \leq 2 - \frac{(1-k)^2}{Ct} + \frac{2(c_M+R)}{t}$;*

(iv) *otherwise, for all $a \in [0, 1]$, the supply chain is coordinated.*

In addition, if $C \leq \frac{(1-k)^2}{2(t+c_M+R)}$, then changing the revenue share a only changes the allocation of the total supply chain profit between the supplier and the manufacturer. If $\frac{(1-k)^2}{2(t+c_M+R)} < C < \frac{(1-k)^2}{t+2(c_M+R+R_M)}$, then in the coordination range $\left(2 - \frac{(1-k)^2}{Ct} + \frac{2(c_M+R+R_M)}{t} < a < 1\right)$, both the manufacturer and the supplier earn larger profits than they would with the wholesale price contract. Consequently, comparing to the wholesale price contract, these revenue-sharing contracts yield a win-win scenario in such a case. Lastly, if $C > \frac{(1-k)^2}{t+2(c_M+R+R_M)}$, when the supply chain is coordinated, the supplier does not invest in innovation, which is the same as the outcome with the wholesale price contract.

Next, how do these contracts compare to each other? Specifically, how do they impact the upstream innovation investment and firms' profits within a supply chain? The answer to this

question can help Apple to understand how to push its display supplier LGD to innovate better displays. In the remainder of the paper, when comparing different contracts, we use superscripts to indicate the contract types. The centralized supply chain (the first-best benchmark), the revenue-sharing contract, the wholesale price contract, and the quality-dependent wholesale price contract are denoted as FB, RS, WP, and QD, respectively.

We first explore the impact of different contracts on the innovation level in a supply chain and examine which contract form is more effective in motivating upstream innovation. Moreover, from the manufacturer's point of view, it is equally important to understand the consequence of pushing the upstream supplier's innovation on his own profit. Is he better off employing the revenue-sharing contract to provide a stronger innovation incentive to the upstream supplier? Interestingly, we find that while the revenue-sharing contract always coordinates the whole channel and maximizes the total supply chain profit, it is not always the best choice for the manufacturer. Corollary 2 presents the results of comparing the centralized case and the three contracts in the innovation level, and the manufacturer's profit.

- Corollary 2** (i) If $C \leq \frac{(1-k)^2}{2(t+c_M+R)}$, then $Q = \frac{1-k}{C}$ in all four cases (the centralized case and the three contracts analyzed), and $\pi_M^{QD} > \pi_M^{RS} = \pi_M^{WP}$;
- (ii) If $\frac{(1-k)^2}{2(t+c_M+R)} < C \leq \frac{(1-k)^2}{t+2(c_M+R+R_M)}$, then $Q^{FB} = Q^{RS} > Q^{WP} = Q^{QD}$, and $\pi_M^{RS} > \pi_M^{WP} = \pi_M^{QD}$;
- (iii) Otherwise, $Q = 0$, and $\pi_M = 0$ in all four cases.

The above results suggest that when the innovation cost is relatively low ($C \leq \frac{(1-k)^2}{2(t+c_M+R)}$), all three contracts can achieve the supply chain optimal innovation level (the first-best benchmark level). In this regime, the revenue-sharing contract is equivalent to the wholesale price contract, because the manufacturer does not share his revenue with the supplier. There is no dou-

ble marginalization effect in this regime because the demand is bounded and the market is fully covered. In contrast, when innovation is relatively costly $\left(\frac{(1-k)^2}{2(t+c_M+R)} < C \leq \frac{(1-k)^2}{t+2(c_M+R+R_M)}\right)$, only the revenue-sharing contract is able to achieve the supply chain optimal investment level in innovation. In other words, both the wholesale price contract and the quality-dependent wholesale price contract suffer from the double marginalization problem and, hence, cannot coordinate the supply chain. Therefore, if Apple wants to incentivize its upstream supplier to invest more in innovation, the revenue-sharing contract is more effective than either the wholesale price contract or the quality-dependent wholesale price contract.

In terms of maximizing the manufacturer's profit, first, there is no single contract form that dominates the other two in all cases. When the innovation cost is low $\left(C \leq \frac{(1-k)^2}{2(t+c_M+R)}\right)$, the quality-dependent wholesale price contract can effectively incentivize the supplier to innovate and also maximize the manufacturer's profit. In this case, the manufacturer extracts all of the supply chain profit, benefiting from its strong channel power, and the supplier receives only her reservation profit. In contrast, the revenue-sharing contract becomes equivalent to the wholesale price contract and the manufacturer is able to obtain only part of the total supply chain profit. These results suggest that when the innovation cost is low, it is important for the manufacturer to secure the right to set the quality-dependent wholesale price. If he can successfully keep the right to set the quality-dependent wholesale price, he can then capture the entire supply chain profit and leave the supplier her reservation profit. It is worth noting that this result depends on the assumption that the manufacturer has the power to choose the contract form. Otherwise, the supplier can refuse a quality-dependent wholesale price contract and revert back to a wholesale price contract.

However, if the quality-dependent wholesale price contract cannot achieve the supply chain optimal innovation level, which occurs when innovation is relatively costly $\left(\frac{(1-k)^2}{2(t+c_M+R)} < C \leq \frac{(1-k)^2}{t+2(c_M+R+R_M)}\right)$, then the revenue-sharing contract is the manufacturer's best option. In this case, the manufacturer

shares the minimum portion of revenue with the supplier and is able to keep all the supply chain profit, leaving the supplier her reservation profit. These results suggest that when the innovation cost is relatively high, the manufacturer should be proactive and offer to share his revenue with the supplier. He can then leave the right to set the wholesale price to the supplier, and still reaps all of the supply chain profit and leave the supplier her reservation profit.

Our finding implies that in order to foster more innovation by LGD and at the same time obtain more profit, Apple should specify technological requirements for displays and set the corresponding wholesale price if LGD's innovation cost is low. Moreover, if LGD's innovation cost is relatively high, then Apple should use the revenue-sharing contract in its relationship with LGD.

It is also worth noting that if the manufacturer is able to choose his favorite contract form based on the innovation cost, the supply chain optimal innovation level is achieved under this optimal contract for the manufacturer.

A policy maker may also be interested in the consumer surplus resulting from different supply chain contracts, and how it compares with the consumer surplus in the centralized supply chain. Actually, consumers benefit from the contract chosen by the manufacturer as well. The consumer surplus is at least $t/4$, as long as the market is fully covered. In addition, because the manufacturer sets the consumer product prices optimally, the consumer surplus never exceeds $t/4$, and is optimized under the manufacturer's optimal contract. This finding implies that if Apple optimizes its contract with LGD, then consumers will also benefit.

5 Extensions: Upstream Competition

5.1 Substitute Suppliers

From the manufacturer's point of view, given the supply chain structure, he can increase his profit by employing the appropriate contract form, i.e., either the revenue-sharing contract or the quality-dependent wholesale price contract, depending on the upstream supplier's innovation cost. However, the manufacturer may not be the one determining the contract form. In this case, it may still be possible for the manufacturer to increase his profit by inviting competition between upstream suppliers. The question is: How does the upstream competition between suppliers affect the manufacturer's profit? In order to answer this question, we extend our model to a supply chain setting with two competing suppliers and one monopolistic manufacturer, similar to the supply chain structure explored by Ozer and Raz (2011).

With the wholesale price contract, in stage 1, supplier 1 sets her wholesale price w_1 and determines her innovation level Q_1 . Then, in stage 2, the competing supplier, supplier 2, sets her wholesale price w_2 and decides on the quality of her product Q_2 .⁷ Finally, observing the wholesale prices and product qualities offered by those two suppliers, the manufacturer decides the prices of the products, and revenues are realized. In the quality-dependent wholesale price contract case, the manufacturer specifies wholesale price menus for the competing suppliers. Observing these wholesale price menus, suppliers decide their innovation levels respectively. Furthermore, the two suppliers have reservation profits R_1 and R_2 respectively. Without loss of generality, we assume that $R_1 \leq R_2$.

The supply chain decisions and profits under upstream competition are stated in the following proposition:

⁷The supply chain decisions and profits remain the same if the suppliers have opportunities to improve their offers, i.e., lowering the wholesale price or improving the quality, after stage 2.

Proposition 2 *Under upstream competition, if $R_2 \leq (1-k)^2/(2C) - t - c_M$, then the wholesale price contract results in the same supply chain decisions and profits as those with the quality-dependent wholesale price contract under upstream monopoly with $R = R_2$, which are given in Proposition 1, and supplier 2 does not invest in innovation, that is, $Q_2^* = 0$; Otherwise, the outcomes are the same as the upstream monopoly case with supplier 1 as the monopolistic supplier, as presented in Proposition 1.*

Under upstream competition, the quality-dependent wholesale price contract results in the same supply chain decisions and profits as those with the quality-dependent wholesale price contract under upstream monopoly with $R = R_1$, which are given in Proposition 1. The other supplier does not invest in innovation, that is, $Q_2^ = 0$.*

With the wholesale price contract, upstream competition strengthens the monopolistic manufacturer's channel power. In order to compete for the manufacturer's order, supplier 1 has to offer a better deal to the manufacturer than what would be offered by a monopolistic supplier. If supplier 2 can offer a product with quality Q_2 at a wholesale price w_2 , which is more attractive to the manufacturer than supplier 1's offering, and still make a profit larger than her reservation profit R_2 , then supplier 2 will choose to do so, and the manufacturer will buy only from supplier 2. In this case, supplier 1 will not be able to recover her innovation cost. Therefore, in equilibrium, supplier 1 offers Q_1 and w_1 such that the manufacturer's profit as given in (5) is maximized subject to the constraint that her own profit as given in (6) is no less than the supplier's higher reservation profit R_2 . This constraint optimization problem is the same as the one faced by the manufacturer with the quality-dependent wholesale price contract under upstream monopoly in choosing the quality Q and the wholesale price w . If supplier 2 is competitive enough ($R_2 \leq (1 - k)^2/(2C) - t - c_M$), then this constraint optimization problem is feasible, and as a result, the manufacturer becomes as if he sets the quality-dependent wholesale price under upstream monopoly. That is, the threat of

competition forces supplier 1 to relinquish more profit to the monopolistic manufacturer. Hence, the upstream competition can be considered to be a substitute for the quality-dependent wholesale price contract from the manufacturer's point of view in such cases. If $R_2 > (1 - k)^2 / (2C) - t - c_M$, then the above mentioned constraint optimization problem has no feasible solution, which means supplier 2 will not participate. Therefore, the supply chain decisions and profits are the same as the upstream monopoly case with supplier 1 as the monopolistic supplier.

When the manufacturer sets the quality-dependent wholesale price, he effectively decides both qualities and wholesale prices subject to the constraint that the supplier who invests in innovation gets at least her reservation profit. The manufacturer is able to extract all of the profit in the supply chain and leave the participating supplier her reservation profit. Upstream competition may increase the manufacturer's channel power. However, with the quality-dependent wholesale price contract, he already has strong channel power; thus, inviting upstream competition does not do much to strengthen his power. Based on the results above, the right to set the quality-dependent wholesale price and the upstream competition have similar effect on the manufacturer's profit. Specifically, if the manufacturer does not have strong channel power to set the quality-dependent wholesale price, inviting competing suppliers helps to increase his channel power as well as his profit.

Our finding suggests that inviting a competing display supplier does not help Apple increase its profit further, if it is already setting the quality-dependent wholesale price for the display supplier LGD. In contrast, if LGD is setting the wholesale price, then having a competing display supplier enables Apple to gain more profits.

However, under upstream competition, neither the wholesale price contract nor the quality-dependent wholesale price contract coordinates the supply chain when innovation is relatively costly. But what is the case in the revenue-sharing contract? Does it coordinate the supply chain as well

as maximize the manufacturer's profit under upstream competition? We answer this question in the following proposition:

Proposition 3 *Under upstream competition, the revenue-sharing contract achieves the supply chain optimal innovation level. The supply chain decisions and profits in equilibrium are:*

(i) If $C \leq \frac{(1-k)^2}{2(t+c_M+R_2)}$, then $Q_1^* = \frac{1-k}{C}$, $Q_2^* = 0$, $p_1^* = \frac{1-k}{C} - \frac{t}{2}$, $w_1^* = \frac{1-k^2}{2C} + R_2$, and $a_1^* = 0$.

In this case, the corresponding profits are $\pi_M = \frac{(1-k)^2}{2C} - c_M - R_2 - \frac{t}{2}$, $\pi_{S1} = R_2$ and

$$\pi_{sc} = \frac{(1-k)^2}{2C} - c_M - \frac{t}{2};$$

(ii) If $\frac{(1-k)^2}{2(t+c_M+R_2)} < C \leq \frac{(1-k)^2}{2(t+c_M+R_1)}$, then $Q_1^* = \frac{1-k}{C}$, $Q_2^* = 0$, $p_1^* = \frac{1-k}{C} - \frac{t}{2}$, $w_1^* = \frac{1-k}{C} - t - c_M$,

and $a_1^* = 0$. In this case, the corresponding profits are $\pi_M = \frac{t}{2}$, $\pi_{S1} = \frac{(1-k)^2}{2C} - c_M - t$ and

$$\pi_{sc} = \frac{(1-k)^2}{2C} - c_M - \frac{t}{2};$$

(iii) If $\frac{(1-k)^2}{2(t+c_M+R_1)} < C \leq \frac{(1-k)^2}{t+2(c_M+R_1+R_M)}$, then $Q_1^* = \frac{1-k}{C}$, $Q_2^* = 0$, $a_1^* = 2 - \frac{(1-k)^2}{Ct} + \frac{2(c_M+R_1)}{t}$,

$w_1^* = \frac{(1-k^2)(1-k)}{C^2t} - \frac{(1-k)(2c_M+2R_1+kt)}{Ct} + c_M + 2R_1 - t$, and $p_1^* = \frac{1-k}{C} - \frac{t}{2}$. In this case, firms'

profits are $\pi_M = \frac{(1-k)^2}{2C} - c_M - R_1 - \frac{t}{2}$, $\pi_{S1} = R_1$ and $\pi_{sc} = \frac{(1-k)^2}{2C} - c_M - \frac{t}{2}$;

(iv) Otherwise, $Q_1^* = Q_2^* = 0$.

If the two suppliers have the same reservation profit, that is, $R_1 = R_2$, then the revenue-sharing contract maximizes the manufacturer's profit.

Under upstream monopoly, the revenue-sharing contract can coordinate the supply chain. However, it may not maximize the manufacturer's profit. Proposition 3 finds that under upstream competition, the revenue-sharing contract not only coordinates the supply chain, but also maximizes the manufacturer's profit if the two suppliers are symmetric. When the innovation cost is low ($C \leq \frac{(1-k)^2}{2(t+c_M+R_2)}$), the manufacturer does not give any revenue to the suppliers, and the revenue-sharing contract is effectively the same as the wholesale price contract. In this case, the existence

of supplier 2 precludes supplier 1 from charging a high wholesale price and enables the manufacturer to receive all of the supply chain profit and to leave supplier 1 with supplier 2's reservation profit. When the innovation cost is relatively low $\left(\frac{(1-k)^2}{2(t+c_M+R_2)} < C \leq \frac{(1-k)^2}{2(t+c_M+R_1)}\right)$, the manufacturer still does not share any revenue with suppliers. However, supplier 2 does not participate because of her high reservation profit, and thus supplier 1 is behaving as a monopolistic supplier. In this case, the revenue-sharing contract does not maximize the manufacturer's profit. However, as supplier 2's reservation profit decreases, this region becomes smaller. Specifically, when the two suppliers are symmetric ($R_1 = R_2$), this region becomes empty. When the innovation cost is relatively high $\left(\frac{(1-k)^2}{2(t+c_M+R)} < C \leq \frac{(1-k)^2}{t+2(c_M+R+R_M)}\right)$, the manufacturer can maximize his profit even without upstream competition. Therefore, the existence of a competing supplier does not help the manufacturer further. Finally, if the innovation cost is so high $\left(C > \frac{(1-k)^2}{t+2(c_M+R+R_M)}\right)$ that even a centralized supply chain cannot make a positive profit, then there is certainly no innovation in a decentralized supply chain.

This result suggests that Apple should consider inviting competition between display suppliers and employing the revenue-sharing contract. By doing so, Apple would be able to provide its display suppliers with enough incentive to innovate, and also to increase its own profit.

5.2 Complementary Components Suppliers

Besides pushing innovation in the hardware, Apple also puts efforts to make sure that its software and the breadth of apps complements the device (Cheng 2012). Because for products like iPad, there exists strong complementarity between the components of the products, e.g., between hardware and software. In this section, we extend our model to capture this complementarity and investigate the impact of the complementarity on innovation and profits. Casadesus-Masanell and Yoffie (2007) analyze the interactions between producers of complementary products, specifically,

Intel and Microsoft, and indicate that both investment levels and profits are higher if they can cooperate. Comparing to their focus on horizontal relationships, we investigate vertical relationships and study how different supply chain contracts affect the innovation and profits.

In this setting, there are two suppliers innovating and then producing complementary components. Let Q_i ($i = 1, 2$) be the quality of supplier i 's component. We assume the corresponding innovation cost to be $CQ_i^2/2$. The quality of the final product Q depends on the qualities of both suppliers' components; specifically, $Q = \sqrt{Q_1Q_2}$. Similar to our base model, the manufacturer sets the product price, and the horizontal product differentiation model is employed to model the consumer demand. To simplify our analysis, we assume $k = 0$, $R = 0$, $R_M = 0$, and $c_M = 0$. Furthermore, in the revenue-sharing contract case, we restrict our attention to cases where the manufacturer offers the same revenue shares to the two suppliers, that is $a_1 = a_2 = a/2$.

We analyze the centralized supply chain (first-best) case, which serves as our benchmark. Then we examine a decentralized supply chain with the three distinct contracts. The supply chain decisions and profits in equilibrium are presented in the following proposition:⁸

Proposition 4 *With complementary components suppliers, the optimal supply chain decisions and profits are:*

(i) *In the centralized supply chain, if $C \leq \frac{1}{2t}$, then $Q_1^* = Q_2^* = Q^* = \frac{1}{2C}$, $p^* = \frac{1}{2C} - \frac{t}{2}$ and*

$$\pi_{sc} = \frac{1}{4C} - \frac{t}{2}; \text{ otherwise, } Q_1^* = Q_2^* = 0.$$

(ii) *In a decentralized supply chain with the wholesale price contract, if $C \leq \frac{1}{6t}$, then $Q_1^* = Q_2^* =$*

$$Q^* = \frac{1}{2C}, p^* = \frac{1}{2C} - \frac{t}{2}, w_1^* = w_2^* = \frac{1}{4C} - \frac{t}{2}, \text{ and firms' profits are } \pi_M = \frac{t}{2}, \pi_{S1} = \pi_{S2} = \frac{1}{8C} - \frac{t}{2}$$

$$\text{and } \pi_{sc} = \frac{1}{4C} - \frac{t}{2}; \text{ otherwise, } Q^* = 0.$$

(iii) *In a decentralized supply chain with the quality-dependent wholesale price contract, if $C \leq \frac{1}{4t}$,*

⁸In a decentralized supply chain, no innovation, i.e., $Q_1 = Q_2 = 0$, is always an equilibrium. However, we focus on equilibria with positive innovation investments, if any, which are (weakly) Pareto-dominant compared to the equilibrium without investment.

then $Q_1^* = Q_2^* = Q^* = \frac{1}{2C}$, $p^* = \frac{1}{2C} - \frac{t}{2}$, $w_1^* = w_2^* = \frac{1}{8C}$, and firms' profits are $\pi_M = \frac{1}{4C} - \frac{t}{2}$, $\pi_{S1} = \pi_{S2} = 0$ and $\pi_{sc} = \frac{1}{4C} - \frac{t}{2}$; otherwise, $Q_1^* = Q_2^* = 0$.

(iv) In a decentralized supply chain with the revenue-sharing contract, if $C \leq \frac{1}{6t}$, then $a^* = 0$, $Q_1^* = Q_2^* = Q^* = \frac{1}{2C}$, $p^* = \frac{1}{2C} - \frac{t}{2}$, $w_1^* = w_2^* = \frac{1}{4C} - \frac{t}{2}$, and firms' profits are $\pi_M = \frac{t}{2}$, $\pi_{S1} = \pi_{S2} = \frac{1}{8C} - \frac{t}{2}$ and $\pi_{sc} = \frac{1}{4C} - \frac{t}{2}$; if $\frac{1}{6t} < C \leq \frac{1}{4t}$, then $a^* = \frac{12Ct-2}{8Ct-1}$, $Q_1^* = Q_2^* = Q^* = \frac{t}{8Ct-1}$, $p^* = \frac{t(3-8Ct)}{16Ct-2}$, $w_1^* = w_2^* = \frac{t(4Ct-1)^2}{(8Ct-1)^2}$, and firms' profits are $\pi_M = \frac{t(1-4Ct)}{16Ct-2}$, $\pi_{S1} = \pi_{S2} = \frac{t(9Ct-1-16C^2t^2)}{2(8Ct-1)^2}$ and $\pi_{sc} = \frac{t(30Ct-3-64C^2t^2)}{2(8Ct-1)^2}$; otherwise, $Q_1^* = Q_2^* = 0$.

In a centralized supply chain, innovation is conducted in the most cost-effective way; that is, the total innovation cost is minimized in achieving the product quality Q . Moreover, if the innovation cost is too high, i.e., $C > \frac{1}{2t}$, there is no product innovation.

In the wholesale price contract case, when the innovation cost is low, because the suppliers set the wholesale prices, they reap the marginal profit of more innovation efforts and leave the manufacturer a constant profit. The manufacturer still receives a positive profit because he determines the price of the final product and can always add a margin on top of the wholesale prices. But when innovation is relatively costly, even though it is optimal for the entire supply chain to invest in innovation, the wholesale price contract cannot provide enough incentive for the suppliers to make innovation investments.

With the quality-dependent wholesale price contract, although the manufacturer is effectively making all supply chain decisions, the supply chain is still not always coordinated due to the double marginalization problem.

Comparing the equilibrium outcomes, we observe that neither the wholesale price contract nor the quality-dependent wholesale price contract always coordinates the supply chain. Rather, they may result in underinvestment in innovation even under complementary components suppliers. This observation demonstrates the robustness of our previous results on the characteristics of

these contracts without complementarity. Furthermore, when the quality-dependent wholesale price contract can achieve the supply chain optimal innovation investment levels, the manufacturer gains all the supply chain profit and leaves the suppliers with their reservation profits. This observation with complementarity is also consistent with our result in the case of one upstream supplier.

However, the revenue-sharing contract does not always coordinate the supply chain in the presence of complementarity. With two complementary components suppliers, coordinating the supply chain becomes harder, especially when the innovation cost is high.

6 Concluding Remarks

We study three widely-used contracts in a supply chain with endogenous upstream innovation. We demonstrate that the revenue-sharing contract coordinates the supply chain, whereas the wholesale price contract and the quality-dependent wholesale price contract may or may not. A manufacturer prefers the revenue-sharing contract when the quality-dependent wholesale price contract does not coordinate the supply chain, and prefers the quality-dependent wholesale price contract otherwise. We extend our model to include competing suppliers and show that inviting upstream competition under the wholesale price contract significantly increases the manufacturer's profit, and has a similar effect to employing the quality-dependent wholesale price contract. We also analyze the three contracts with complementary components suppliers and show that most of our results are robust.

Our findings provide some guidance to managers of manufacturers on how to encourage their suppliers to invest more in innovation, and simultaneously gain more profit. For example, if innovation is relatively costly, Apple should consider implementing the revenue-sharing contract with his display supplier before she innovates, whereas if innovation cost is low, Apple should consider offering a quality-dependent wholesale price contract to the supplier or invite competition between

display suppliers.

We focus on the impact of contracts on *upstream* innovation in a supply chain in this paper. However, in some cases, the manufacturer can also invest to improve the quality of the product. Incorporating the *downstream* product innovation decision as well as the *upstream* one can engender several new interesting research questions. However, these are beyond the scope of our paper, and we leave them for future research.

In conclusion, innovation is a key competency for many firms operating in high-tech industries and novel product industries. Our work helps in understanding the impact of various supply chain contracts on encouraging innovation as well as on downstream firms' profits. We hope that our study will stimulate new avenues of research on supply chain contracts and product innovation in supply chains.

7 Acknowledgement

The authors are thankful to Mark Ferguson, Glen Schmidt and Gil Souza as well as anonymous senior editor and three reviewers for their constructive feedback and thoughtful comments. They also thank the new product development, innovation and sustainability workshop participants at Kelley School of Business, Indiana University for valuable comments and discussions.

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Appendix

Proof of Proposition 1: The proofs of the centralized supply chain, the wholesale price contract, and the revenue sharing contract cases are outlined in the text and thus omitted here.

The results of the quality-dependent wholesale price contract case are derived by solving a constraint optimization problem, i.e., maximizing the manufacturer's profit as given in (5) subject to the constraint that the supplier's profit (6) is no less than R . We solve this constraint optimization problem as follows:

First, denote $w^*(Q)$ as the smallest nonnegative w that solves $\pi_S(w; Q) = R$. So if the manufacturer chooses an innovation level Q , then it should choose $w^*(Q)$ if it exists. We first analyze $w^*(Q)$ and then solve the optimization problem.

Assume that $Q \geq \frac{c_M + R}{1-k}$, since the supply chain won't generate enough profit to cover the supplier's reservation profit otherwise. Depending on the quality Q , if $w^*(Q)$ exists, it can fall into two regions: Region 1 if $w^*(Q) \leq Q - t - c_M$, or Region 2 if $w^*(Q) > Q - t - c_M$.

Region 1: $w^*(Q)$ is in Region 1 if and only if $\pi_S(Q - t - c_M; Q) \geq R$; that is, $Q(1-k) - t - c_M - \frac{CQ^2}{2} \geq R$. In this case, the corresponding $w^*(Q)$ is $kQ + R + \frac{CQ^2}{2}$.

Region 2: Suppose that $w^*(Q)$ is in Region 2. Then there must exist a wholesale price $Q - t - c_M < w \leq Q - c_M$, such that $\pi_S(w; Q) = R$. Notice that $\pi_S(Q - t - c_M; Q) = Q(1-k) - t - c_M - \frac{CQ^2}{2} < 0$ and $\pi_S(Q - c_M; Q) = -\frac{CQ^2}{2} < 0$. Furthermore, the maximizer of $\pi_S(w; Q)$ is $\frac{Q(1+k) - c_M}{2}$. To ensure that $w^*(Q)$ is in Region 2, we must have $Q - t - c_M < \frac{Q(1+k) - c_M}{2} \leq Q - c_M$ and $\pi_S(\frac{Q(1+k) - c_M}{2}; Q) \geq R \geq 0$; that is,

$$\frac{c_M}{1-k} \leq Q < \frac{2t - c_M}{1-k}, \text{ and} \quad (\text{A.1})$$

$$h(Q) = \pi_S\left(\frac{Q(1+k) - c_M}{2}; Q\right) = \frac{(Q(1-k) - c_M)^2}{4t} - \frac{CQ^2}{2} \geq 0. \quad (\text{A.2})$$

Next, we show that the optimal Q will never be chosen such that $w^*(Q)$ is in Region 2. Suppose not. Then $w^*(Q)$ is the smaller root of $\pi_S(w; Q) = R$, which is $\frac{Q(1+k) - c_M - \sqrt{(Q(1-k) - c_M)^2 - 2t(CQ^2 + 2R)}}{2} \geq 0$. Plugging it into the manufacturer's profit function (5) and taking derivative over Q , we obtain

$$\text{sign}(\pi'_M(w^*(Q), Q)) = \text{sign} \left\{ 1 - k + \frac{Q((1-k)^2 - 2Ct) - c_M(1-k)}{\sqrt{(Q(1-k) - c_M)^2 - 2t(CQ^2 + 2R)}} \right\}. \quad (\text{A.3})$$

So if $Q((1-k)^2 - 2Ct) \geq c_M(1-k)$, then $\pi'_M(w^*(Q), Q) > 0$. Consider the following three cases:

Case 1: if $(1-k)^2 > 2Ct$, then $h''(Q) > 0$. So it must be that $Q \geq \frac{c_M(1-k)+c_M\sqrt{2Ct}}{(1-k)^2-2tC}$ or $Q \leq \frac{c_M(1-k)-c_M\sqrt{2Ct}}{(1-k)^2-2tC}$ in order for condition (A.2) to be satisfied. At the same time, condition (A.1) needs to be satisfied as well. Consider $Q \geq \frac{c_M+R}{1-k} > \frac{c_M}{1-k} > \frac{c_M(1-k)-c_M\sqrt{2Ct}}{(1-k)^2-2tC}$, we must have $Q \geq \frac{c_M(1-k)+c_M\sqrt{2Ct}}{(1-k)^2-2tC} > \frac{c_M(1-k)}{(1-k)^2-2tC}$ to satisfy both conditions. Therefore, $Q((1-k)^2 - 2Ct) \geq c_M(1-k)$; that is, $\pi'_M(w^*(Q), Q) > 0$. Consequently, this Q cannot be optimal.

Case 2: if $(1-k)^2 = 2Ct$, then $h(Q) = -\frac{c_M(2Q(1-k)-c_M)}{4t}$. Since $Q \geq \frac{c_M}{1-k}$ by condition (A.1), $h(Q) \leq -\frac{c_M^2}{4t} < 0$; that is, condition (A.2) is violated. Hence, this cannot be satisfied in equilibrium.

Case 3: if $(1-k)^2 < 2Ct$, then $h''(Q) < 0$. So it must be that $\frac{c_M}{1-k-\sqrt{2tC}} \leq Q \leq \frac{c_M}{1-k+\sqrt{2tC}}$ in order for condition (A.2) to be satisfied. However, then $Q \leq \frac{c_M}{1-k+\sqrt{2tC}} < \frac{c_M}{1-k}$; that is, condition (A.1) is violated. Hence, this cannot be satisfied in equilibrium.

Therefore, the optimal Q is either in Region 1 or equal to zero. In Region 1, the manufacturer's profit as a function of Q under the optimal wholesale price $w^*(Q)$ is $\pi_M(Q) = Q(1-k) - \frac{t}{2} - \frac{CQ^2}{2} - c_M - R$. So the optimal innovation level is $\frac{1-k}{C}$. If $Q = \frac{1-k}{C}$ is in Region 1, we must also have that $w^*(Q) \leq Q - t - c_M$, that is, $C \leq \frac{(1-k)^2}{t+2(c_M+R)}$. And the manufacturer's optimal profit is $\pi_M(\frac{1-k}{C}) = -\frac{t}{2} - c_M + \frac{(1-k)^2}{2C} - R$, which is positive if $C \leq \frac{(1-k)^2}{t+2(c_M+R)}$. Therefore, if $C \leq \frac{(1-k)^2}{t+2(c_M+R)}$, then the optimal innovation level is $\frac{1-k}{C}$, and 0 otherwise. Then we have the equilibrium innovation level and the corresponding wholesale price as given in the proposition. ■

Proof of Corollary 1: The proof is outlined in the text and thus omitted here. ■

Proof of Corollary 2: The proof follows directly by comparing the innovation levels, the manufacturer's profits and the consumer surplus given in Proposition 1. ■

Proof of Proposition 2: We start by proving the following Lemma:

Lemma A.1 *As long as $Q_1 - p_1 \neq Q_2 - p_2$, the manufacturer will not be able to sell positive quantities of both products.*

Proof of Lemma A.1: Suppose the manufacturer sells two product and $Q_1 - p_1 \neq Q_2 - p_2$. Without loss of generality, assume that $Q_1 - p_1 > Q_2 - p_2$. Denote a consumer's distance to the store as d . Then her utility of purchasing product i is $Q_i - p_i - td$ and $Q_1 - p_1 - td > Q_2 - p_2 - td$, which means that the consumer strictly prefers product 1. Notice that this preference is location independent, that is, all consumers have the same preference. Therefore, no consumer will buy product 2. ■

In the wholesale price contract case, we first prove that there is no equilibrium where both suppliers are able to sell positive quantities. Suppose not. Then as shown in Lemma A.1, it must be the case that $Q_1 - p_1 = Q_2 - p_2$. Depending on the wholesale prices, there are two possible alternatives:

1. $w_1 \neq w_2$. Without loss of generality, we assume $w_1 > w_2$. The manufacturer then can strictly increase his profit by selling only the more profitable product, i.e., product 1. Therefore, this cannot be an equilibrium.
2. $w_1 = w_2$. Denote the total demands for the two products as q_1 and q_2 respectively. Note that $w_1 > kQ_1$ to insure that supplier 1 has nonnegative profit. Let $\delta = \frac{q_2(w_1 - kQ_1)}{2(q_1 + q_2)}$. If supplier 1 chooses the wholesale price $w'_1 = w_1 - \delta$, instead of w_1 , the manufacturer will sell only product 1 at a price no larger than the original price, i.e., $p'_1 \leq p_1$. Therefore, $q'_1 \geq q_1 + q_2$. Supplier 1's profit becomes $q'_1(w_1 - \delta - kQ_1) \geq (q_1 + q_2)(w_1 - \delta - kQ_1) > q_1(w_1 - Q_1)$; that is, supplier 1 can obtain more profit. Therefore, this cannot be an equilibrium, either.

Consequently, in equilibrium, only one supplier invests in innovation and the manufacturer sells one product only. If $C \leq \frac{(1-k)^2}{2(t+c_M+R_2)}$, as the two suppliers are symmetric except for the reservation profit, the wholesale price and quality offered by supplier 1 must optimize the manufacturer's profit as given in (5) subject to the constraint that her profit as given in (6) is no less than R_2 . Otherwise, supplier 2 could offer a better deal to attract the manufacturer and gets positive profit. As a result, the supply chain decisions and profits in equilibrium in this setting are the same as those under a quality-dependent wholesale price set by the manufacturer with upstream monopoly. If $\frac{(1-k)^2}{2(t+c_M+R_2)} < C \leq \frac{(1-k)^2}{2(t+c_M+R_1)}$, then supplier 2 does not participate, and thus the outcomes are the same as the wholesale price contract case with supplier 1 as the monopolistic supplier.

In the quality-dependent wholesale price contract case, suppose that in equilibrium, both suppliers make positive investments in innovation. Then both products must be sold at positive quantities

so that both suppliers get at least their reservation profits; that is, $q_1 > 0$, and $q_2 > 0$. Based on Lemma A.1, we have $Q_1 - p_1 = Q_2 - p_2$. Without loss of generality, assume that product 1 is more profitable for the manufacturer, i.e., $p_1 - w_1(Q_1) \geq p_2 - w_2(Q_2)$. Because consumers have the same preference over the two products, if the manufacturer sells only product 1 with quality Q_1 at price p_1 , the total quantity sold will be the same; that is, the new demand for product 1 is $q'_1 = q_1 + q_2 > q_1$. The manufacturer can offer a new wholesale price $w'_1(Q_1) = \frac{(w_1(Q_1) - kQ_1)q_1}{q'_1} + kQ_1$ to supplier 1. As $w'_1(Q_1) - kQ_1 = \frac{(w_1(Q_1) - kQ_1)q_1}{q'_1} < w_1(Q_1) - kQ_1$, we have $w'_1(Q_1) < w_1(Q_1)$. In addition, supplier 1's new profit is $(w'_1(Q_1) - kQ_1)q'_1 - \frac{CQ_1^2}{2} = (w_1(Q_1) - kQ_1)q_1 - \frac{CQ_1^2}{2}$, i.e., supplier 1's profit remains the same. Therefore, the manufacturer can offer supplier 1 a lower wholesale price to incentivize her to invest in innovation (note that supplier 1's profit remains the same) and make more profit. Hence, there is at most one supplier making positive investment in equilibrium. Because and the two suppliers are the same except for that $R_1 \leq R_2$, the manufacturer will choose to incentivize the supplier with the lower reservation profit to innovate in order to keep more profit to himself. Therefore, The supply chain decisions and profits in equilibrium are the same as that under upstream monopoly with $R = R_1$. ■

Proof of Proposition 3: If $C \leq \frac{(1-k)^2}{2(t+c_M+R_2)}$, then by setting a equal to zero, the manufacturer can make the contracts effectively the same as the wholesale price contracts. As shown in Proposition 2, the manufacturer obtains the supply chain optimal profit less the supplier's higher reservation profit R_2 . This is the best outcome for the manufacturer, because for any $a \in [0, 1]$, supplier 2 will offer Q_2 and w_2 such that she gets at least her reservation profit R_2 , and supplier one has no reason to leave more profits to the manufacturer. Therefore, in equilibrium, the manufacturer sets $a = 0$ and the outcomes are the same as those presented in Proposition 2.

If $\frac{(1-k)^2}{2(t+c_M+R_2)} < C \leq \frac{(1-k)^2}{2(t+c_M+R_1)}$, then based on equation (10), in order to incentivize supplier 2 to participate, the manufacturer has to set $a \geq 2 - (1-k)^2/(2C) + 2(c_M + R_2)/t$. In such cases, the best outcome for the manufacturer is to get the supply chain optimal profit less R_2 , that is, $(1-k)^2/(2C) - c_M - R_2 - t/2$. In contrast, if $a < 2 - (1-k)^2/(2C) + 2(c_M + R_2)/t$, then supplier 2 will not participate and the outcomes are the same as the case where supplier 1 is the monopolistic supplier. In such cases, as shown in Proposition 1, the best revenue share is $a = 0$, and the corresponding manufacturer's profit is $t/2$, which is greater than $(1-k)^2/(2C) - c_M - R_2 - t/2$. Therefore, the optimal revenue share is $a = 0$ and the outcomes are the same as those in the

monopoly supplier case as shown in Proposition 1.

If $\frac{(1-k)^2}{2(t+c_M+R_1)} < C \leq \frac{(1-k)^2}{t+2(c_M+R_1+R_M)}$, as shown in Proposition 1, the manufacturer can obtain the supply chain optimal profit less the lower supplier's reservation profit R_1 even with upstream monopoly. Because this outcome is the best that the manufacturer can get, he just contracts with one supplier and reaps all the remaining profits.

If $C > \frac{(1-k)^2}{t+2(c_M+R_1+R_M)}$, as the centralized supply chain does not invest in innovation, it is impossible to have positive innovation, with the manufacturer gets at least his reservation profit and the innovating supplier gets her reservation profit.

Proof of Proposition 4: First, we define $c(Q)$ as the minimum total innovation cost needed to achieve quality Q , that is,

$$\begin{aligned} c(Q) = \min_{Q_1, Q_2} & \left(\frac{CQ_1^2}{2} + \frac{CQ_2^2}{2} \right) \\ \text{s.t. } & \sqrt{Q_1 Q_2} = Q. \end{aligned} \tag{A.4}$$

Then $c(Q) = CQ^2$ as shown in the following lemma.

Lemma A.2 *The optimal way to achieve quality Q is to set $Q_1 = Q_2 = Q$, and the minimum cost $c(Q)$ is CQ^2 .*

Proof. For all (Q_1, Q_2) such that $\sqrt{Q_1 Q_2} = Q$, we have the total innovation cost $\frac{C}{2}(Q_1^2 + Q_2^2) \geq CQ_1 Q_2 = CQ^2$, with the inequality being equal if and only if $Q_1 = Q_2 = Q$. ■

The Centralized Supply Chain

In the centralized supply chain, the total gross profit (not including innovation costs) of the supply chain is fully specified by the product price p and quality Q . Therefore, the profit maximization problem is to choose (Q, p) to maximize the difference between the total gross profit and the minimum innovation cost $c(Q)$. Then the total supply chain profit can be derived similar to equation (1). Solving this optimization problem, we obtain the results.

The Wholesale Price Contract

In the wholesale price contract case, similar to the monopoly supplier case, we first derive supplier

1's profit as a function of her wholesale price w_1 and innovation effort Q_1 .

$$\pi_{S1}(w_1, Q_1; w_2, Q_2) = \begin{cases} w_1 - \frac{CQ_1^2}{2}, & \text{if } w_1 \leq \sqrt{Q_1Q_2} - t - w_2; \\ \frac{(\sqrt{Q_1Q_2} - w_1 - w_2)w_1}{t} - \frac{CQ_1^2}{2}, & \text{if } \sqrt{Q_1Q_2} - t - w_2 < w_1 < \sqrt{Q_1Q_2} - w_2; \\ -\frac{CQ_1^2}{2}, & \text{otherwise.} \end{cases} \quad (\text{A.5})$$

Supplier 2's profit function is similar. We claim that any equilibria with positive product quality must satisfy $w_1 + w_2 = \sqrt{Q_1Q_2} - t$.

- (i) If $w_1 < \sqrt{Q_1Q_2} - t - w_2$, then supplier 1 can increase w_1 to increase her profit. Thus this cannot happen in equilibrium.
- (ii) If $\sqrt{Q_1Q_2} - t < w_1 + w_2 < \sqrt{Q_1Q_2}$, then the first order conditions must be satisfied. By solving the first order conditions for both suppliers, we have $Q_1 = Q_2 = w_1 = w_2 = 0$, which falls out of the region. Therefore, there is no equilibrium in this region.
- (iii) If $w_1 + w_2 \geq \sqrt{Q_1Q_2}$, then the only equilibrium is $Q_1 = Q_2 = 0$.

We then use the necessary conditions to derive the outcomes of possible equilibrium with a positive product quality. Plugging $w_1(Q_1; w_2, Q_2) = \sqrt{Q_1Q_2} - t - w_2$ into (A.5), we obtain

$$\pi_{S1}(w_1(Q_1; w_2, Q_2), Q_1; w_2, Q_2) = \sqrt{Q_1Q_2} - t - w_2 - \frac{CQ_1^2}{2}. \quad (\text{A.6})$$

Furthermore, Q_1 must satisfy the first order condition. Solving the first order condition, we have $Q_1 = \left(\frac{Q_2}{4C^2}\right)^{\frac{1}{3}}$. Similarly, $Q_2 = \left(\frac{Q_1}{4C^2}\right)^{\frac{1}{3}}$. Solving these two equations together gives us a unique positive solution $Q_1^* = Q_2^* = \frac{1}{2C}$. In this case, the symmetric wholesale prices are $w_1^* = w_2^* = \frac{1}{4C} - \frac{t}{2}$.

Next, we check the conditions under which $(w_i^*, Q_i^*; w_j^*, Q_j^*)$ can constitute an equilibrium. First, each supplier must get a nonnegative profit; that is, $\pi_{S1}\left(\frac{1}{4C} - \frac{t}{2}, \frac{1}{2C}; \frac{1}{4C} - \frac{t}{2}, \frac{1}{2C}\right) = \frac{1-4tC}{8C} \geq 0$, which is satisfied if and only if $C \leq \frac{1}{4t}$. Second, each supplier must have no incentive to deviate. The first order condition for Q_i is used in deriving the expression and thus is satisfied. We now check whether the supplier has an incentive to choose a different wholesale price, take her own quality decision and the other supplier's decisions as given. From equation (A.7), supplier i 's profit decreases if she decrease her wholesale price and thus has no incentive to do so. In order for supplier i not willing to increase her wholesale price, we must have that $\lim_{w_i \rightarrow w_i^*+} \left(\pi_{Si}(w_i^*, Q_i^*; w_j^*, Q_j^*) - \pi_{Si}(w_i, Q_i^*; w_j^*, Q_j^*) \right) / (w_i^* - w_i) \leq 0$, that is, $\frac{12Ct-2}{8Ct} \leq 0$, which is

satisfied if and only if $C \leq \frac{1}{6t}$. We then further verify that $(w_i^*, Q_i^*; w_j^*, Q_j^*)$ is indeed an equilibrium if $C \leq \frac{1}{6t}$ by checking that the Karush-Kuhn-Tucker necessary and sufficient conditions are indeed satisfied.

Therefore, if $C \leq \frac{1}{6t}$, then $Q_1^* = Q_2^* = \frac{1}{2C}$ and $w_1^* = w_2^* = \frac{1}{4C} - \frac{t}{2}$; otherwise $Q_1^* = Q_2^* = 0$.

The Quality-dependent Wholesale Price Contract

In the quality-dependent wholesale price contract case, let $\pi_M(w, Q)$ be the manufacturer's profit under the optimal product price given the total wholesale price ($w = w_1 + w_2$) and the quality of the final product. Let $\pi_{S_i}(w_i, Q_i)$ be supplier i 's profit given w_i and Q_i . Then the manufacturer needs to choose $(w_i, Q_i), i \in \{1, 2\}$ to maximize $\pi_M(w_1 + w_2, \sqrt{Q_1 Q_2})$ subject to the constraints that $\pi_{S_i}(w_i, Q_i) \geq 0$ for $i = 1, 2$. Denote this constrained maximization problem and its optimal value as CM and V , respectively. Let $\pi_S(w, Q)$ be the total of suppliers' profits given the total wholesale price and the quality (assuming that the suppliers minimize their total innovation cost). Let CM' be the optimization problem of choosing w and Q to maximize $\pi_M(w, Q)$ subject to the constraint $\pi_S(w, Q) \geq 0$ and let V' be the corresponding optimal value. Similar to the proof of Proposition 1, one can solve CM' ; then, its maximizer (w^*, Q^*) is as follows: If $C \leq \frac{1}{4t}$, then $Q^* = \frac{1}{2C}$, $w^* = \frac{1}{4C}$; otherwise, $Q^* = w^* = 0$.

For any (w, Q) that satisfies $\pi_S(w, Q) \geq 0$, we have $w_1 = w_2 = \frac{w}{2}$ and $Q_1 = Q_2 = Q$ such that $\pi_{S_i}(w_i, Q_i) \geq 0$ for $i = 1, 2$. Therefore, it follows that $V \leq V'$. Let $w_1^* = w_2^* = \frac{w^*}{2}$ and $Q_1^* = Q_2^* = Q^*$. One can then show that $(w_1^*, w_2^*, Q_1^*, Q_2^*)$ is feasible for CM and $\pi_M(w_1^* + w_2^*, \sqrt{Q_1^* Q_2^*}) = \pi_M(w^*, Q^*) = V' \geq V$. Therefore, $(w_1^*, w_2^*, Q_1^*, Q_2^*)$ is a maximizer for CM . Plugging them into the profit functions and solving for the optimal product price, we obtain the results presented in the proposition.

The Revenue-sharing Contract

In the revenue-sharing contract case, denote $a = a_1 + a_2$ as the total revenue portion that the manufacturer shares with the suppliers, then $a_1 = a_2 = a/2$, as we assume $a_1 = a_2$. Then the manufacturer's profit is the same as the one in equation (7), and thus the optimal product price is

the same as in equation (8). And the supplier i 's profit is

$$\pi_{S_i}(w_i, Q_i; a_i, Q_j) = \begin{cases} \frac{a\sqrt{Q_i Q_j}}{2} - \frac{at}{4} - \frac{CQ_i^2}{2} + w_i & \text{if } w_i \leq (\sqrt{Q_i Q_j} - t)(1 - a) - w_j; \\ \left(\frac{a}{2} \frac{\sqrt{Q_i Q_j}(1-a) + w_i + w_j}{2(1-a)} + w_i\right) \frac{\sqrt{Q_i Q_j}(1-a) - w_i - w_j}{t(1-a)} - \frac{CQ_i^2}{2} & \text{if } (\sqrt{Q_i Q_j} - t)(1 - a) - w_j < w_i \leq \sqrt{Q_i Q_j}(1 - a) - w_j; \\ -\frac{CQ_i^2}{2} & \text{otherwise.} \end{cases} \quad (\text{A.7})$$

We claim that any equilibria with positive product quality must satisfy $w_1 + w_2 = \sqrt{Q_1 Q_2} - t$.

(i) If $w_1 < (\sqrt{Q_1 Q_2} - t)(1 - a) - w_2$, then supplier 1 can increase w_1 to increase her profit. Thus this cannot happen in equilibrium.

(ii) If $(\sqrt{Q_1 Q_2} - t)(1 - a) < w_1 + w_2 < (1 - a)\sqrt{Q_1 Q_2}$, then the first order conditions must be satisfied. By solving the first order conditions for both suppliers, we have $Q_1 = Q_2 = w_1 = w_2 = 0$, which falls out of the region. Therefore, there is no equilibrium in this region.

(iii) If $w_1 + w_2 \geq (1 - a)\sqrt{Q_1 Q_2}$, then the only equilibrium is $Q_1 = Q_2 = 0$.

We then use the necessary conditions to derive the outcomes of possible equilibrium with a positive product quality. Plugging $w_i(Q_i; w_j, Q_j) = (\sqrt{Q_i Q_j} - t)(1 - a) - w_j$ into (A.7), we obtain

$$\pi_{S_i}(w_i(Q_i; w_j, Q_j), Q_i; w_j, Q_j) = \frac{(2 - a)\sqrt{Q_i Q_j}}{2} - \frac{4 - 3a}{4}t - w_j - \frac{CQ_i^2}{2}. \quad (\text{A.8})$$

Furthermore, Q_i must satisfy the first order condition. Solving the two first order conditions together gives us a unique positive solution $Q_1^*(a) = Q_2^*(a) = \frac{2-a}{4C}$. In this case, the symmetric wholesale prices are $w_1^*(a) = w_2^*(a) = \frac{(1-a)(2-a-4Ct)}{8C}$.

Next, we analyze when $Q_1^*(a), Q_2^*(a), w_1^*(a), w_2^*(a)$ constitutes an equilibrium. First, each supplier must get a nonnegative profit, that is, $\pi_{S_i}(w_i^*(a), Q_i^*(a); w_j^*(a), Q_j^*(a)) \geq 0$, which is equivalent to

$$a - 8Ct + 2 \geq 0. \quad (\text{A.9})$$

Second, each supplier must have no incentive to deviate. The first order condition for Q_i is used in deriving the expression and thus is satisfied. We now check whether the supplier has an incentive to

choose a different wholesale price, take her own quality decision and the other supplier's decisions as given. From equation (A.7), supplier i 's profit decreases if she decrease her wholesale price and thus has no incentive to do so. In order for supplier i not willing to increase her wholesale price, we must have that

$$\lim_{w_i \rightarrow w_i^*(a)^+} \frac{\pi_{Si}(w_i^*(a), Q_i^*(a); w_j^*(a), Q_j^*(a)) - \pi_{Si}(w_i, Q_i^*(a); w_j^*(a), Q_j^*(a))}{w_i^*(a) - w_i} \leq 0, \quad (\text{A.10})$$

that is,

$$\frac{a - 8aCt + 12Ct - 2}{8Ct(1 - a)} \leq 0. \quad (\text{A.11})$$

If $C \leq \frac{1}{6t}$, then conditions (A.9) and (A.11) hold. And we can verify that the Karush-Kuhn-Tucker necessary and sufficient conditions are satisfied for supplier i 's ($i = 1, 2$) optimization problem. Therefore, $Q_1^*(a), w_1^*(a), Q_2^*(a), w_2^*(a)$ is an equilibrium for all $a \in [0, 1]$. Then the manufacturer's profit as a function of the revenue share is $\pi_M(a) = \frac{t(1-a)}{2}$. So the optimal a is zero and the manufacturer's corresponding profit is $\pi_M^* = t/2$.

If $\frac{1}{6t} < C \leq \frac{1}{4t}$, then conditions (A.11) is satisfied, but condition (A.11) holds if and only if $a \geq 1 - \frac{1-4Ct}{8Ct-1}$. And we can verify that the Karush-Kuhn-Tucker necessary and sufficient conditions are satisfied. Therefore, $Q_1^*(a), w_1^*(a), Q_2^*(a), w_2^*(a)$ is an equilibrium if and only if $a \in [1 - \frac{1-4Ct}{8Ct-1}, 1]$. Then the manufacturer's profit as a function of the revenue share is

$$\pi_M(a) = \begin{cases} 0, & \text{if } a < 1 - \frac{1-4Ct}{8Ct-1}; \\ \frac{t(1-a)}{2}, & \text{otherwise.} \end{cases} \quad (\text{A.12})$$

So the manufacturer's optimal revenue share is $a^* = 1 - \frac{1-4Ct}{8Ct-1}$, and his corresponding profit is $\pi_M^* = \frac{t-4Ct^2}{16Ct-2}$.

If $C > \frac{1}{4t}$, then condition (A.11) holds if and only if $a \geq 1 - \frac{1-4Ct}{8Ct-1} > 1$. So $Q_1^*(a), w_1^*(a), Q_2^*(a), w_2^*(a)$ is not an equilibrium for any $a \in [0, 1]$, which means there is no equilibrium with positive innovation levels.

Plugging the equilibrium revenue share a^* into $Q_1^*(a), w_1^*(a), Q_2^*(a), w_2^*(a)$ gives us the equilibrium innovation levels and wholesale prices. We then plug these supply chain decisions into equation (A.7) to get the suppliers' profits. ■