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Flexible versus Committed and Specific versus Uniform: Wholesale Price Contracting in A Supply Chain with Downstream Process Innovation

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Abstract

If buyers are asymmetric in terms of their operating costs, researchers and managers broadly agree that the supplier can optimize her/his own profit by offering the more efficient buyer a higher price. In this paper, we develop a game theoretical model to investigate the interaction between one supplier and two asymmetric buyers within a supply chain. We formulate buyers operating costs as a function of their process innovation levels, which implies that they can reduce the unit operating cost via investments in process innovation in the long run. Our research demonstrates that the uniform wholesale price (UWP) is always preferred over the buyer-specific wholesale price by the supplier because of the effect of innovation stimulation. The optimal timing of pricing is contingent on the level of market demand variance. If two buyers have the same ability to reduce their operating costs via process innovation, the UWP strategy forms a win-win-win situation to the supplier and two buyers. Our results provide the supplier with suggestions regarding when to adopt the UWP strategy and how to enhance downstream innovation performance within the supply chain.

Keywords: supply chain management; pricing; process innovation; market uncertainty

1. Introduction

The supplier of a homogeneous product/component (e.g., P&G or Intel) generally sells to multiple buyers, and then these buyers compete in the same market. The prior literature on pricing policy (reviewed in the next section) has enormous consensus that the supplier is better off with a buyer-specific wholesale price (BSWP), i.e., charging each buyer a specific wholesale price, if buyers are asymmetric in terms of

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their operating costs. We acknowledge that this view is right in the short run. However, it is worth noting that few firms are born to be more efficient than competitors (Plambeck and Taylor 2005).

Innovation in a supply chain involves changes in products, processes, or services that can reduce costs or improve efficiency (Roy, Sivakumar et al. 2004). Therefore, the most important way for firms to be more efficient is to reduce their operating costs via process innovation continually. As is well known, Walmart is one of the most efficient retailers in the world, and it can be found from its history (see walmart.com) that this company is dedicated to the investment in process innovation, e.g., in 1987, Walmart installed the largest private satellite communication system to link its operations through voice, data, and video communication; In 2017, Walmart launched Store No 8, a tech incubator, which will change the operations of the retail industry through the use of new technologies like autonomous vehicles, virtual reality, drone delivery and personalized shopping (see storeno8.com). By the end of 2025, more than 580,000 autonomous mobile robots (AMR) will be used in warehouses to fulfill customer orders (Forbes, 2019). Another example is Kroger, a leading American retailing company. In the past few years, it pioneered a faster checkout process named QueVision that greatly reduced the time customers wait in line to check out (see Kroger.com). The competitor, Amazon, followed by Amazon Go in America. Amazon Go is a new kind of store with no checkout required (see Amazon.com). Especially Covid-19 makes more retailers focus on continuous innovation, like developing new grocery delivery services and technology to achieve healthier and safer purchasing. The possibility of downstream innovation (i.e., innovation adopted by downstream buyers, i.e., retailers in our motivational examples) that leads to a unit cost reduction in the long run should be considered by the upstream supplier when deciding its pricing strategy.

In this paper, we aim to develop a general understanding of the desirability of a BSWP and a uniform wholesale price (UWP), i.e., charging all buyers the same wholesale price, from the supplier's perspective considering downstream process innovation. Although uniform wholesale price contracts are observed in practice (Ferrari and Verboven 2012), wholesale price discrimination is commonly adopted in many important markets, including markets such as petroleum distribution, steel, heavy trucking, tobacco, and pharmaceuticals (Villas-Boas 2009). Specifically, in the retail market, after merging with another retailer, one of the largest German retail chains learned that the suppliers were charging five percent higher wholesaler price to the retail chain than to the merging partner. Moreover, anecdotal evidence suggests that suppliers indeed have an incentive to adjust their wholesale prices according to downstream innovation. For example, Dell invested in developing a new generation of personal computer that is less expensive to assemble; after observing Dell's cost-efficient design, Intel and other powerful suppliers respond by setting wholesale prices higher than they otherwise would (Gilbert and Cvsa 2003).

The above examples illustrate that the wholesale price strategy is not a trivial issue for the supplier, especially considering the possibility of downstream innovation. In this context, we answer the following research questions: (1) What is the supplier's optimal pricing strategy, a BSWP strategy or a UWP strategy? (2) What is the optimal timing for the supplier to determine the pricing strategy? (3) What are the impacts of the suppliers pricing strategy on downstream buyers' profitability? Although there are also other non-linear wholesale pricing mechanisms that could be adopted, we focus on the constant wholesale price because of its pervasiveness in practice (Vakharia and Wang 2014). The UWP can signal that all buyers are being treated equally, which is critical if buyers concern about price fairness (Chen and Cui 2013, Wu and Niederhoff 2014, Li, Cui et al. 2019). However, to isolate the strategic issue related to the suppliers preference for pricing, we do not consider the impact of fairness concern.

By considering two buyers that can simultaneously decide on the level of process innovation in the model, our findings suggest that the supplier's UWP strategy is superior to the BSWP strategy. This is because the BSWP strategy blunts the buyer's incentive to invest in process innovation and ultimately reduces the supplier's profits. The findings make a substantial contribution to the literature on buyer-specific price discrimination and innovation decisions in supply chain management. In addition, the optimal timing of pricing depends on the degree of variability in market demand. When market uncertainty is sufficiently low, the supplier commit to the wholesale price in advance and the optimal wholesale price is independent of the parameters associated with downstream innovation. Our findings can help suppliers set optimal pricing policies.

The remainder of this paper is organized as follows. Section 2 reviews related literature and highlight our contributions. Section 3 formulates the model. Section 4 analyzes the optimal decisions of all players in different sub-games contingent on the supplier's pricing strategy. Section 5 identifies the dominant pricing strategy for the supplier and examines its impacts on downstream innovation and buyers' profitability. Section 6 describes the key implications and directions for future research. Appendix A contains the proofs of all analytical results.

2. Literature review

Our work mainly draws on and contributes to two streams of research: (1) the literature on the supplier's pricing strategy when there is more than one buyer; (2) the literature on managing innovation in a supply chain. These two streams are largely independent of each other. Our work is one of a few papers that bridge the gap between them.

Buyer-specific price discrimination has been a topic of significant research interests for decades, although it is governed by the primary US law, the RobinsonCPatman Act of 1936. Numerous papers in the economics literature have examined the impact of price discrimination on welfare, see, e.g., Yoshida (2000) and O'Brien (2014). In the field of operations management, it is confirmed that the supplier will be better off with a BSWP strategy in a wide variety of settings, see, e.g., Dukes, Gal-Or et al. (2006), Cui, Raju et al. (2008), and Wu and Zhou (2019). Letting the supplier offer a uniform wholesale price to all buyers, as required by the RobinsonCPatman Act, Ingene and Parry (1995) design a quantity-discount schedule to coordinate the channel. With the same requirement, Wu, Chen et al. (2012) investigate the supplier's pricing decisions in six power structures that characterize exclusively horizontal competition between downstream buyers and vertical competition between the supplier and buyers. Vakharia and Wang (2014) find that the total supply chain profit is greater when the supplier adopts a UWP strategy as compared to a BSWP strategy, and propose a unique UWP contract with a slotting allowance or a side payment to coordinate the channel. Jin, Wu et al. (2017) find that under a BSWP strategy, a downstream retailer has a stronger incentive to introduce a store brand. Lou, He et al. (2021) investigate a BSWP strategy when two competing retailers have different brand reputations. However, all these papers consider the suppliers pricing in the short run and ignore the possibility of downstream innovation in the long run.

There is a growing amount of literature on supply chain management that incorporates the decision on innovation. Innovation is extensively investigated in the supply chain, e.g., Bellamy, Ghosh et al. (2014), Sabri, Micheli et al. (2018) and Niu, Zeng et al. (2021). The innovation may be undertaken by the upstream firm or/and the downstream firm, and the investment may be incurred by a single firm or shared by both firms. There are some papers that have studied how innovation affects upstream and downstream business relationships, e.g., Hall and Andriani (2003), Roy and Sivakumar (2010). Vanderwerf (1992) shows that downstream firms tend to innovate when the supply industrial is concentrated. Kim (2000) analyzes the downstream buyers strategy to coordinate the supplier's innovation that can eventually lead to a cost reduction. Gilbert and Cvsa (2003) show that the supplier can stimulate downstream innovation by simply committing to price in advance. If both firms have innovation opportunities to enhance the market demand, Gurnani, Erkoc et al. (2007) consider three different decision-making structures and discuss the optimal configuration from each firms perspective. Bhaskaran and Krishnan (2009) design three mechanisms revenue sharing, investment sharing, and innovation sharing to improve the performance of collaborative innovation in the supply chain. Ge, Hu et al. (2014) demonstrate that the upstream firm and the downstream firm can achieve win-win in a supply chain where they first cooperate in innovation and then decide the production quantity according to a wholesale price contract. Usta, Erhun et al. (2014) find that the downstream buyer's full commitment to invest in innovation may enable a proprietary component supplier to license the technology. Ashok, Day et al. (2018) find no direct association between the level of buyer dissatisfaction and process innovation. Reimann, Xiong et al. (2019) investigate the optimal process innovation level for remanufacturing in a closed-loop supply chain, and find that there might be an overinvestment problem in process innovation. Xu, Liu, Huang, Zhou, and Wei (2022) consider a two competing supply chains with one supplier and one manufacturer each to explore the innovation information sharing strategy of the manufacture. Although this research stream has generated fruitful insights, it mostly focuses on a bilateral monopoly. In the current study, we consider two downstream buyers (one or both have process innovation opportunities) and examine the suppliers preference between a BSWP and a UPW. We find that a UPW can stimulate downstream buyers to set a higher process innovation level and hence benefit the entire supply chain because of the lower operational costs.

The supplier's pricing considering downstream innovation is relatively understudied. To the best of our knowledge, Degraba (1990) makes the first attempt in this direction. Two downstream buyers move first by choosing their process innovation level with the knowledge of whether the supplier will employ a UWP. However, these two buyers are symmetric in terms of their process innovation abilities, and the market demand is deterministic. Degraba (1990) examines only the impact of the supplier's pricing strategy on the optimal innovation level, production quantities, and welfare. Similarly, Inderst and Valletti (2009) assume that the supplier is a constrained monopolist with the threat of demand-side substitution, and demonstrate that the UWP benefits consumers in the short run but reduces consumer surplus in the long run. Brunner (2013) and Li (2013) pay attention to this direction as well, but both consider the BSWP strategy only. Our paper makes a substantial contribution to the literature on the suppliers pricing strategy for the supply chain with downstream innovation. The unique contribution of our work lies in that we examine the preference of a BSWP and a UWP from the perspective of the supplier in an uncertain market, and find that the UWP is a dominant strategy in light of downstream innovation: if the demand uncertainty is low enough, the supplier is better off by committing to a uniform wholesale price in advance of the downstream buyers innovation; otherwise, the supplier should commit to a UWP strategy, but announce the wholesale price after demand information is revealed.

3. Model

In order to examine the impact of the supplier offering either a BSWP or a UWP to downstream buyers, we consider a simple two-echelon supply chain consisting of one supplier and two buyers (indexed by $i = 1, 2$, $j = 3 - i$). Game theory is used in this paper to investigate the interaction within the supply chain, which has been widely used in the literature on supply chain management (Li and Zhou 2016, Wu and Zhou 2017, Huang, Meng et al. 2019). The supplier provides a homogeneous product/component to buyers at a constant unit production cost, which is normalized to 0. The primary decision for the supplier is to set a constant per unit wholesale price for each buyer $\{w_1, w_2\}$.

Each buyer makes her/his order quantity decision to satisfy downstream demand in the same market (Jin, Hu et al. 2019). We assume that the inverse demand function is linear in the quantity offered (Arya, Mittendorf et al. 2008). In particular, let q_i be Buyer i's quantity and define the market-clearing price as follows:

$$p_i = \frac{1}{2}\left(a+\varepsilon\right) - q_i - bq_j, \tag{1}$$

where $(a + \varepsilon)$ represents the uncertain market potential, a is a positive constant and ε is an additive error term, with density $f(\varepsilon)$, mean of 0, standard deviation of σ, and positive support in the range $(\varepsilon_{\min}, \varepsilon_{\max})$, $b \in (0, 1)$ is the competitive intensity between the two buyers.

In our model, at the very beginning of the planning horizon, we assume that two buyers are symmetric in terms of their operating costs but asymmetric in terms of their process innovation opportunities. Buyer i can reduce her/his marginal cost from c to $(c - r_i\theta_i)$ by investing $\frac{1}{2}I{\theta_i}^2$. Here, r_i is the maximum amount of cost reduction that can be achieved via process innovation by Buyer i, and without loss of generality, we have $0 \leq r_2 \leq r_1 \leq c$; θ_i is Buyer i's process innovation level, and I is the innovation cost parameter. Following the relevant literature on innovation management (Bhaskaran and Krishnan 2009, Reimann, Xiong et al. 2019, Hong, Li et al. 2020), we assume that I is high enough, i.e., $I > I_{\min}$, [1] such that the optimal process innovation level in the model is always less than 1. It implies that the marginal cost of Buyer i cannot be less than $c - r_i$ within the limits of current technology, regardless of how much the buyer invests. It is worth noting that process innovation as a long-run investment must be made before the realization of demand uncertainty. To avoid trivial situations, we require that the cost parameter is not prohibitively high, i.e., $c < a/2$, such that for every realization of the demand there always exist equilibrium solutions with which all firms obtain positive profits.

Based on the above assumptions, the supplier's, Buyer 1's and Buyer 2's profit functions can be written as

$$\pi_s w_2 = w_1 q_1 + w_2 q_2, \tag{2}$$

$$\pi_i = \left(p_i - w_i - c + r_i\theta_i\right) q_i - \frac{1}{2}I{\theta_i}^2, i = 1, 2. \tag{3}$$

Our model is developed to analyse the supplier's optimal pricing strategy from two dimensions: the form and the timing of pricing. As for the form of pricing, the supplier decides to use either a BSWP

[1] The detailed proofs of all parameter constraints are provided in Appendix B.

strategy or a UWP strategy, denoted by the superscript B and U, respectively. Provided that the supplier adopts a UWP strategy, we have w_1 is always equal to . As for the timing of pricing, the supplier decides to set wholesale prices before or after downstream process innovation. Figure 1 shows the timeline of events in the model. Process innovation is a strategic decision, and the investment $\frac{1}{2}I\theta^2$ is sunk once if the innovation level is determined; whereas pricing is a tactical decision, and it can be changed easily. Therefore, the supplier has the flexibility to price the product after the buyer's process innovation, which we refer to as a flexible pricing strategy, denoted by the superscript F. In addition, we are interested in the strategy under which the supplier commits to wholesale prices before the buyers invest in process innovation. The latter strategy is referred to as a committed pricing strategy, denoted by the superscript C.

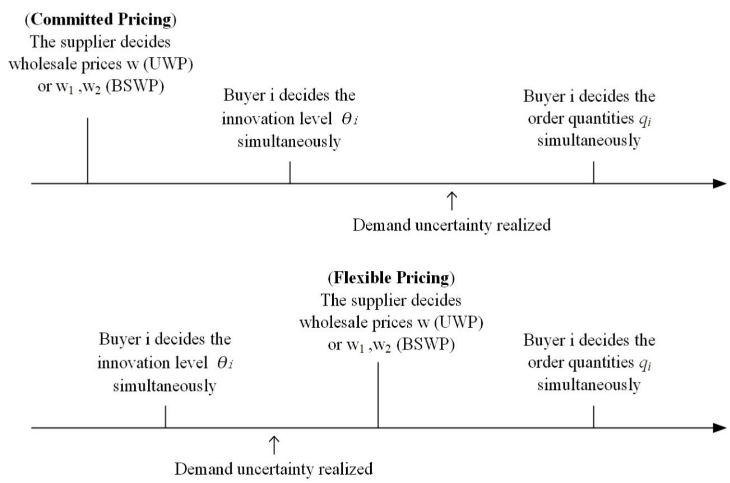

Fig. 1: Timing of the Game

Consequently, combining the form and the timing of the supplier's pricing strategy, we obtain four sub-games between the supplier and the two buyers. We first analyse the optimal solutions in each sub-game, and then we identify the supplier pricing strategy by comparing its profits in all sub-games.

4. Analysis

In this section, we solve for the optimal decisions of all players in each sub-game using backward induction, which is followed by a sensitivity analysis on all model parameters. The first scenario is the sub-game with flexible BSWP, in which the supplier charges each buyer a specific price after observing the buyer's process innovation. The second scenario is the sub-game with flexible UWP, in which the supplier charges two buyers the same price after observing buyers process innovation. The third scenario is the sub-game with committed BSWP, in which the supplier charges each buyer a specific price before observing the buyers process innovation. The fourth scenario is the sub-game with committed UWP, in which the supplier charges two buyers the same price before observing buyers' process innovation.

4.1. Flexible BSWP

At the final stage of this sub-game, the two buyers are given the realization of demand uncertainty (ε), the wholesale prices (w_1^{FB} and w_2^{FB}), and each buyer's process innovation level (θ_i^{FB}), and determine their order quantities simultaneously and separately to maximize their profits, as shown in Equation (3). It is easy to prove that $\pi_i^{FB}\left(\varepsilon, w_i^{FB}, w_j^{FB}, \theta_i^{FB}, \theta_j^{FB}, q_j^{FB}; q_i^{FB}\right)$ is concave in q_1^{FB} and q_2^{FB}, respectively. From first-order conditions, we have

$$q_i^{FB} = \frac{(2-b)(a-2c+\varepsilon) + 4r_i\theta_i^{FB} - 2br_j\theta_j^{FB} - 4w_i^{FB} + 2bw_j^{FB}}{2(4-b^2)}. \tag{4}$$

With the anticipation of the two buyers' optimal responses as above, the supplier sets the wholesale prices (w_1^{FB} and w_2^{FB}) to maximize the following profit function

$$\begin{aligned}\pi_s^{FB}\left(\varepsilon, \theta_1^{FB}, \theta_2^{FB}; w_1^{FB}, w_2^{FB}\right) = & \tfrac{(a+\varepsilon-2c)(w_1^{FB}+w_2^{FB})}{2(2+b)} \\ & + \tfrac{(2r_1\theta_1^{FB}-br_2\theta_2^{FB}-2w_1^{FB}+2bw_2^{FB})w_1^{FB}-(br_1\theta_1^{FB}-2r_2\theta_2^{FB}+2w_2^{FB})w_2^{FB}}{4-b^2}\end{aligned}. \tag{5}$$

It is easy to prove that Equation (5) is concave in both w_1^{FB} and w_2^{FB}. Thus, we have the suppliers optimal wholesale prices concerning the realization of demand and downstream innovation are

$$w_i^{FB} = \frac{a+\varepsilon}{4} - \frac{c}{2} + \frac{r_i\theta_i^{FB}}{2}. \tag{6}$$

In line with the literature (Degraba 1990, Vakharia and Wang 2014), we confirm that the supplier has an incentive to charger a higher wholesale price to the more cost-efficient buyer after observing downstream innovation; that is, $w_1^{FB} > w_2^{FB}$ if $r_1\theta_1^{FB} > r_2\theta_2^{FB}$, vice versa.

At the time of making the process innovation investment, Buyer i anticipates these responses for every realization of demand and seeks to maximize the expected profit. By substituting Equations (4) and (6) into Equation (3), and integrating over ε, Buyer i's expected profit can be expressed as

$$E\left(\pi_i^{FB}\left(\theta_i^{FB}\right)\right) = \frac{\left(2a-4c-ab+2bc+4r_i\theta_i^{FB}-2br_j\theta_j^{FB}\right)^2}{16(2-b)^2(2+b)^2} + \frac{\sigma^2}{16(2+b)^2} - \frac{1}{2}I\left(\theta_i^{FB}\right)^2. \tag{7}$$

With the assumption $I > I_{\min}$, it can be easily proven that $E\left(\pi_i^{FB}\left(\theta_i^{FB}\right)\right)$ is concave. Thus, we can get Buyer i's optimal process innovation level in this sub-game.

$$\theta_i^{FB*} = \frac{(a-2c)\left((2+b)(2-b)^2 I - {r_j}^2\right) r_i}{2(4-b^2)\left((4-b^2)^2 I - 2\left({r_i}^2+{r_j}^2\right)\right) I + 2{r_i}^2{r_j}^2}. \tag{8}$$

Substituting θ_i^{FB*} back into Equations (4) and (6) and integrating over ε give the expected flexible wholesale prices and the expected order quantities, which are shown in the first column of Table 1.

Table 1: Comparison of equilibrium solutions under different pricing strategies in the basic model

	$Case FB$	$Case FU$
θ_i^*	$\frac{(a-2c)\left((2+b)(2-b)^2I-{r_j}^2\right)r_i}{2\left(4-b^2\right)\left(\left(4-b^2\right)^2I-2\left({r_i}^2+{r_j}^2\right)\right)I+2{r_i}^2{r_j}^2}$	$\frac{\left(2(2+b)(2-b)^2I-(6+b){r_j}^2\right)(a-2c)(6+b)r_i}{16\left(4-b^2\right)^3I^2-2\left(\left(4-b^2\right)\left({r_i}^2+{r_j}^2\right)I-{r_i}^2{r_j}^2\right)(6+b)^2}$
$E\left[w_i^*\right]$	$\frac{\left(\left(4-b^2\right)^2I-b{r_i}^2-2{r_j}^2\right)(a-2c)\left(4-b^2\right)I}{4\left(4-b^2\right)\left(\left(4-b^2\right)^2I-2\left({r_i}^2+{r_j}^2\right)\right)I+4{r_i}^2{r_j}^2}$	$\frac{\left(4(2+b)(2-b)^2I-(6+b)\left({r_i}^2+{r_j}^2\right)\right)(a-2c)(2-b)(2+b)^2I}{16\left(4-b^2\right)^3I^2-2\left(\left(4-b^2\right)\left({r_i}^2+{r_j}^2\right)I-{r_i}^2{r_j}^2\right)(6+b)^2}$
$E\left[q_i^*\right]$	$\frac{\left((2-b)^2(2+b)I-{r_j}^2\right)(a-2c)\left(4-b^2\right)I}{4\left(4-b^2\right)\left(\left(4-b^2\right)^2I-2\left({r_i}^2+{r_j}^2\right)\right)I+4{r_i}^2{r_j}^2}$	$\frac{\left(2(2+b)(2-b)^2I-(6+b){r_j}^2\right)(a-2c)\left(4-b^2\right)I}{8\left(4-b^2\right)^3I^2-\left(\left(4-b^2\right)\left({r_i}^2+{r_j}^2\right)I-{r_i}^2{r_j}^2\right)(6+b)^2}$

	$Case C$
θ_i^*	$\frac{(a-2c)\left((2+b)(2-b)^2I-4{r_j}^2\right)r_i}{\left(4-b^2\right)\left(\left(4-b^2\right)^2I-8\left({r_i}^2+{r_j}^2\right)\right)I+16{r_i}^2{r_j}^2}$
$E\left[w_i^*\right]$	$\frac{a-2c}{4}$
$E\left[q_i^*\right]$	$\frac{\left((2+b)(2-b)^2I-4{r_j}^2\right)(a-2c)\left(4-b^2\right)I}{4\left(4-b^2\right)\left(\left(4-b^2\right)^2I-8\left({r_i}^2+{r_j}^2\right)\right)I+64{r_i}^2{r_j}^2}$

4.2. Flexible UWP

In this sub-game, the supplier is to offer a uniform wholesale price to the two buyers after observing their process innovation. For the sake of clarity, we denote $w_1^{FU} = w_2^{FU} = w^{FU}$. At the final stage, consistent with the sub-game of flexible BSWP, we have

$$q_i^{FU} = \frac{2a + 2bc + (2-b)\,\varepsilon - ab - 4c + 4r_i\theta_i^{FU} - 2br_j\theta_j^{FU} - 2\,(2-b)\,w^{FU}}{2\,(4-b^2)}. \tag{9}$$

With the anticipation of buyers' optimal responses as above, the supplier's profit function turns out to be

$$\pi_s^{FU}(\varepsilon, \theta_1^{FU}, \theta_2^{FU}; w^{FU}) = \frac{\left(a + \varepsilon - 2c + r_1\theta_1^{FU} + r_2\theta_2^{FU} - 2w^{FU}\right) w^{FU}}{2+b}. \tag{10}$$

From the first condition, we have the optimal uniform wholesale price

$$w^{FU} = \frac{a+\varepsilon}{4} - \frac{c}{2} + \frac{r_1\theta_1^{FU} + r_2\theta_2^{FU}}{4}. \tag{11}$$

Following from Equations (6) and (11), it is shown that, for the given levels of process innovation, the optimal uniform wholesale price w^{FU} falls in between two buyer-specific wholesale prices.

Finally, when it comes to the first stage of this sub-game, substituting Equations (9) and (11) into Equation (3) and integrating over ε give Buyer is expected profit

$$\begin{aligned} E\left(\pi_i^{FU}\left(\theta_i^{FU}\right)\right) = &-\tfrac{\left(8(4-b^2)^2 I-(6+b)^2 r_i{}^2\right)(\theta_i^{FU})^2}{16(4-b^2)^2} \\ &+\tfrac{2\left(2a+2bc-ab-4c-(2+3b)r_j\theta_j^{FU}\right)(6+b)r_i\theta_i^{FU}}{16(4-b^2)^2} \\ &+\tfrac{\left(2a+2bc-ab-4c-(2+3b)r_j\theta_j^{FU}\right)^2+(2-b)^2\sigma^2}{16(4-b^2)^2} \end{aligned} \tag{12}$$

With the assumption $I > I_{\min}$, $E\left(\pi_i^{FU}\left(\theta_i^{FU}\right)\right)$ is concave in θ_i^{FU}. From the first-order condition, we have

$$\theta_i^{FU*} = \frac{\left(2\left(2+b\right)\left(2-b\right)^2 I-\left(6+b\right)r_j{}^2\right)\left(a-2c\right)\left(6+b\right)r_i}{16(4-b^2)^3 I^2-2\left(\left(4-b^2\right)\left(r_i{}^2+r_j{}^2\right)-r_i{}^2 r_j{}^2\right)\left(6+b\right)^2}. \tag{13}$$

Substituting θ_i^{FU*} back into Equations (9) and (11) and integrating over ε give the expected flexible wholesale prices and the expected order quantities in this sub-game, which are shown in the second column of Table 1.

4.3. Committed BSWP

In this sub-game, at the final stage, the two buyers determine their order quantities to maximize their profit functions. At the second stage, with anticipation of the two buyers' optimal order quantities, each buyer maximizes her/his expected profit by deciding the process innovation level taking the wholesale prices as given. By substituting the two buyers' optimal order quantities and integrating over ε, each buyer's expected profit function is

$$\begin{aligned} E\left(\pi_i^C\left(w_i^C, w_j^C; \theta_i^C, \theta_j^C\right)\right) = &-\tfrac{(4-b^2)^2 I-8r_i{}^2}{2(4-b^2)^2}\left(\theta_i^C\right)^2 \\ &+\tfrac{2\left(2a-ab+2bc-4c-2br_j\theta_j^C-4w_i^C+2bw_j^C\right)r_i}{(4-b^2)^2}\theta_i^C \\ &+\tfrac{\left(2a-ab+2bc-4c-2br_j\theta_j^C-4w_i^C+2bw_j^C\right)^2+(2-b)^2\sigma^2}{4(4-b^2)^2} \end{aligned} \tag{14}$$

With the assumption $I > I_{\min}$, $E\left(\pi_i^C\left(w_1^C, w_2^C; \theta_i^C\right)\right)$ is concave in θ_i^C. From the first-order condition, we have

$$\theta_i^C = \frac{2r_i\left(\left(4-b^2\right)\left(2a+2bc-ab-4c-4w_i^C+2bw_j^C\right)I-4r_j{}^2\left(a-2c-2w_i^C\right)\right)}{2\left(4-b^2\right)\left(\left(4-b^2\right)^2 I-8\left(r_i{}^2+r_j{}^2\right)\right)I+16r_i{}^2 r_j{}^2}. \tag{15}$$

At the first stage of this sub-game, the supplier's problem is to determine the committed wholesale prices. With the anticipation of the two buyers' process innovation level, the order quantities, and the demand uncertainty, the suppliers expected profit is

$$E\left(\pi_s^C\left(w_1^C, w_2^C\right)\right) = \frac{(4-b^2)\begin{pmatrix} \left(4-b^2\right)\left(2a+2bc-ab-4c-4w_1^C+4bw_2^C\right)I \\ -4{r_2}^2\left(a-2c-2w_1\right) \end{pmatrix} Iw_1^C}{2(4-b^2)\left((4-b^2)^2 I-8({r_1}^2+{r_2}^2)\right)I+32{r_1}^2{r_2}^2} + \frac{(4-b^2)((4-b^2)(2a+2bc-ab-4c-4w_2^C)I-4{r_1}^2(a-2c-2w_2^C))Iw_2^C}{2(4-b^2)\left((4-b^2)^2 I-8({r_1}^2+{r_2}^2)\right)I+32{r_1}^2{r_2}^2} \tag{16}$$

Because Equation (16) is concave in both w_1^C and w_2^C, from the first-order conditions, we have the optimal wholesale prices in this sub-game

$$w_i^{C*} = \frac{a-2c}{4}. \tag{17}$$

The above solutions reveal that before downstream innovation, even if the supplier can charge a BSWP, the supplier is better off by committing to a UWP. This finding is consistent with the literature that proves the supplier's optimal strategy is to commit to a static price over multiple periods, see, e.g., Stokey (1979), Hart and Tirole (1988), and Borgs, Candogan et al. (2014).This is because under the committed pricing strategy, the supplier commits to wholesale prices before the buyers invest in process innovation, and wholesale prices and process innovation level are determined before demand uncertainty is realized. Therefore, if the supplier charges the buyer a higher wholesale price, the buyer is willing to invest less. Then based on each buyers' expected process innovation level, the supplier has no incentive to charge a BSWP. More interestingly, this is also the reason that the optimal wholesale price is independent of the two buyers' process innovation parameters (r_i and I). Thus, even the supplier does not know the downstream buyers' innovation ability, (s)he can commit to the optimal price.

The expected process innovation level and order quantities in this sub-game are shown in the third column of Table 1.

4.4. *Committed UWP*

In this sub-game, at the final stage, the two buyers determine their order quantities to maximize their profit functions. At the second stage, with anticipation of buyers optimal order quantities, each buyer maximizes her/his expected profit by deciding the process innovation level taking the UWP as given. By substituting buyers' optimal order quantities and integrating over ε, Buyer i's expected profit function is equal to the profit function in Equation (14) with the same wholesale price, i.e., $w_1^C = w_2^C = w^C$.

With the assumption $I > I_{\min}$, $E\left(\pi_i^C\left(w^C; \theta_i^C\right)\right)$ is concave in θ_i^C. From the first-order condition, we have $\theta_i^C\left(w^C\right)$, which is similarly equal to the innovation level in Equation (15) with $w_1^C = w_2^C = w^C$.

At the first stage of this sub-game, the supplier's problem is to determine a committed UWP. With anticipation of the two buyers' process innovation levels, the order quantities, and the demand uncertainty, we can obtain the suppliers expected profit, which is concave in w^C. From the first-order condition, we have the optimal committed UWP is equal to the price in Equation (17). Therefore, under the committed pricing strategy, the supplier always determines same wholesale prices due to two buyers' expected process innovation level, then all results in the sub-game with a committed UWP strategy are identical to those in the sub-game with a committed BSWP strategy.

5. Comparison and discussion

In this section, based on the results shown in Table 1, we first compare the optimal process innovation levels and the optimal wholesale prices in all sub-games. It is easy to obtain the following two Corollaries.

The following results are obtained through a comparison of consumer surplus in different scenarios.

THEOREM 1*.In each sub-game, we have $\theta_1^* \geq \theta_2^*$; and for each buyer, we have $\theta_i^{C*} > \theta_i^{FU*} > \theta_i^{FB*}$.*

Buyer 1 is more efficient than Buyer 2 in process innovation, i.e., $r_1 \geq r_2$. Therefore, in a certain sub-game, we always have Buyer 1's process innovation level is higher than Buyer 2's process innovation level. For each buyer, the optimal process innovation level is heavily influenced by the suppliers pricing strategy. In the sub-game with a flexible pricing strategy, that is the sub-games with flexible BSWP and flexible UWP, the more Buyer i invests in process innovation, the higher the wholesale price for her/him is. Such an opportunistic behavior of the supplier creates a hold-up problem that makes Buyer i underinvest. Therefore, Buyer i always invests the most in the sub-game with a committed pricing strategy where the supplier seems to ignore the possibility of downstream innovation. With a flexible BSWP strategy, the wholesale price $E\left[w_i^{FB*}\right]$ is increasing in θ_i only, while with the flexible UWP strategy, $E\left[w_i^{FU*}\right]$ is increasing in both θ_i and θ_j. Thus, the flexible BSWP strategy blunts downstream buyers' incentives to invest in process innovation compared with the flexible UWP strategy. As a result, $\theta_i^{FU*} > \theta_i^{FB*}$.

THEOREM 2*.$E\left[w_1^{C*}\right] < \min\left\{E\left[w_1^{FU*}\right], E\left[w_1^{FB*}\right]\right\}$ and $E\left[w_2^{C*}\right] < E\left[w_2^{FB*}\right] < E\left[w_2^{FU*}\right]$.*

This finding reveals that buyers pay the lowest wholesale price in the sub-game with a committed pricing strategy. This is because of that given $\theta_i = 0$, these optimal wholesale prices $E\left[w_i^*\right]$ in all sub-games are the same. $E\left[w_i^{C*}\right]$ is independent of θ_i, while $E\left[w_i^{FU*}\right]$ and $E\left[w_i^{FB*}\right]$ are increasing in θ_i, so $E\left[w_i^{C*}\right]$ is the lowest wholesale price for Buyer i. We interpret the economic intuition behind this finding as follows. Downstream process innovation will enhance the efficiency of the supply chain. If the supplier adopts a flexible pricing strategy, (s)he can directly benefit from the enhanced efficiency by charging a high wholesale price. However, if the supplier adopts a committed pricing strategy, a high wholesale price charged before downstream innovation will discourage buyers investment. Thus, to stimulate downstream innovation, the supplier should charge a relatively low wholesale price in the sub-game with a committed pricing strategy.

Next, we identify the suppliers optimal pricing strategy by comparing her/his expected profits in these sub-games , which is characterized by the following proposition.

Proposition 1. *There exists a threshold of market demand variance* T *such that for* $\sigma^2 \leq \mathrm{T}$, $E\left[\pi_s^C\right] \geq E\left[\pi_s^{FU}\right] > E\left[\pi_s^{FB}\right]$, *while for* $\sigma^2 > \mathrm{T}$,$E\left[\pi_s^{FU}\right] > \max\left\{E\left[\pi_s^C\right], E\left[\pi_s^{FB}\right]\right\}$.

The optimal timing of pricing is dependent on the level of market demand variance: the supplier prefers to commit to prices before downstream innovation if the demand uncertainty is low enough; otherwise, the supplier is better off by committing to a UWP strategy but postponing the announcement of prices until the demand uncertainty is revealed.

In Appendix C, we also examine the impacts of other parameters, i.e., a, b, c, r_1 and r_2, on the supplier's optimal choice of the pricing strategy. The results show that the supplier prefers a committed pricing strategy if (i) the market size a is sufficiently large, or (ii) the competitive intensity b is sufficiently low, or (iii) the unit cost c is sufficiently low, or (iv) the potential of process innovation r_i is sufficiently large; otherwise, the supplier prefers a flexible pricing strategy.

Finally, we examine the impact of the supplier's UWP strategy on the buyers profitability.

Proposition 2. *The UWP strategy is always beneficial to Buyer 1 (who is more efficient in process innovation).*

It can be seen from Equations (8) and (9), the supplier's incentive to offer a higher wholesale price to the more cost-efficient buyer certainly erodes the reward of downstream innovation, and then Buyer 1 should reduce the investment, which shrinks the total channel profit. The UPW strategy can solve this problem well. Although the supplier shares a smaller portion, i.e., $E\left[w_1^{C*}\right] < \min\left\{E\left[w_1^{FU*}\right], E\left[w_1^{FB*}\right]\right\}$, Buyer 1's incentive to invest in process innovation is enhanced, and the channel profit is increased. As a result, the UPW strategy forms a win-win outcome for the supplier and Buyer 1.

Proposition 3. *The UWP strategy is beneficial to Buyer 2 (who is less efficient in process innovation) when $r_2 > r_1\sqrt{b}$.*

Buyer 2 can also benefit from the committed UWP strategy if the market uncertainty is high enough. However, the supplier then does not commit to prices. The UPW strategy reduces Buyer 2's expected profit if Buyer 1 is a more cost-efficient buyer. The reason for this finding is straightforward. With the UPW strategy, Buyer 2 may be offered a higher wholesale price, while the rival, Buyer 1, will be offered a lower wholesale price and invests more in process innovation. All these impacts are detrimental to Buyer 2.

6. Conclusions

The wholesale price is the key determinant of the volume of orders received by the supplier, which heavily impacts her/his profitability. Moreover, the wholesale price is a significant determinant of the market price, which in turn impacts the profitability and market shares of buyers (Vakharia and Wang 2014). In this paper, we investigate the supplier's optimal pricing strategy from two dimensions: the form and the timing.

Researchers and managers have long viewed the BSWP as a strategy to optimize the supplier's profit. Consistent with the prior literature, we confirm that the supplier has the incentive to offer a higher wholesale price to the more efficient buyer (after the buyers investment in process innovation). In practice, although BSWP is governed by the RobinsonCPatman Act, in recent years, there still are firms being found guilty of violating the act (Luchs, Geylani et al. 2010). But this paper makes a substantial contribution to the literature and the practice by demonstrating that the UWP is a dominant strategy for the supplier considering downstream innovation. The BSWP would blunt buyers' incentive to invest in process innovation, and finally reduce the supplier's profit. The optimal timing of pricing depends on the level of market demand variance. When the market uncertainty is low enough, the supplier commits to the price in advance, and the optimal price is independent of parameters related to downstream innovation. Our analytical results provide clear guidelines on the suppliers optimal pricing policy.

All these results are preserved if two buyers have the same opportunity of process innovation, i.e., $r_1 = r_2$. It is worth noting that, equilibrium process innovation levels of buyers are then the same, and the supplier would offer the same wholesale price after downstream innovation. However, if buyers anticipate that the supplier may adopt a BSWP strategy, they invest less in process innovation. This finding further highlights the importance of committing to the UWP strategy before buyers choose their process innovation levels.

There are several potential avenues for future research stemming from our investigation. Firstly, a natural extension of our research is to compare other types of wholesale pricing mechanisms (such as the quantity discount) to the UWP. Another issue of interest could be to examine how competing suppliers' price considering downstream innovation, which means adding a new supplier into our model. Thirdly, when the market uncertainty is high enough, the optimal UWP is dependent on parameters related to downstream innovation. Thus, a fruitful direction is to consider the information asymmetry on downstream innovation abilities.

References

Arya, A., Mittendorf, B., Sappington, D. E. M., 2008. The Make-or-Buy Decision in the Presence of a Rival: Strategic Outsourcing to a Common Supplier. *Management Science*, 54(10),1747-1758.

Ashok, M., Day, M., Narula, R., 2018. Buyer (dis)satisfaction and process innovation: The case of information technology services provision. *Industrial Marketing Management*, 68,132-144.

Bellamy, M. A., Ghosh, S., Hora, M., 2014. The influence of supply network structure on firm innovation. *Journal of Operations Management*, 32(6), 357-373.

Bhaskaran, S. R., Krishnan, V., 2009. Effort, Revenue, and Cost Sharing Mechanisms for Collaborative New Product Development. *Management Science*, 55(7), 1152-1169.

Borgs, C., Candogan, O., Chayes, J., Lobel, I., Nazerzadeh, H., 2014. Optimal Multiperiod Pricing with Service Guarantees. *Management Science*, 60(7), 1792-1811.

Brunner, M., 2013. Wholesale price discrimination with interdependent retailers. *Spectrum*, 35(4), 1009-1037.

Chen, Y., Cui, T. H., 2013. The Benefit of Uniform Price for Branded Variants. *Marketing Science*, 32(1), 36-50.

Cui, T. H., Raju, J. S., Zhang, Z. J., 2008. A Price Discrimination Model of Trade Promotions. *Marketing Science*, 27(5), 779-795.

Degraba, P., 1990. INPUT MARKET PRICE-DISCRIMINATION AND THE CHOICE OF TECHNOLOGY. *American Economic Review*, 80(5), 1246-1253.

Dukes, A. J., Gal-Or, E., Srinivasan, K., 2006. Channel bargaining with retailer asymmetry. *Journal of Marketing Research*, 43(1), 84-97.

Ferrari, S., Verboven, F., 2012. Vertical control of a distribution networkuan empirical analysis of magazines. *Rand Journal of Economics*, 43(1), 26-50.

Forbes., 2019. The Top 10 Technology Trends In Retail: How Tech Will Transform Shopping In 2020. Available at https://www.forbes.com/sites/bernardmarr/2019/11/25/the-top-10-technology-trends-in-retail-how-tech-will -transform-shopping-in-2020/?sh=2b89230a4e03 (accessed date October 1, 2021)

Ge, Z., Hu, Q., Xia, Y., 2014. Firms' R&D Cooperation Behavior in a Supply Chain. *Production and Operations Management*, 23(4), 599-609.

Gilbert, S. M., Cvsa, V., 2003. Strategic commitment to price to stimulate downstream innovation in a supply chain. *European Journal of Operational Research*, 150(3), 617-639.

Gurnani, H., Erkoc, M., Luo, Y., 2007. Impact of product pricing and timing of investment decisions on supply chain co-opetition. *European Journal of Operational Research*, 180(1), 228-248.

Hall, R., Andriani, P., 2003. Managing knowledge associated with innovation. *Journal of Business Research*, 56(2), 145-152.

Hart, O. D., Tirole, J., 1988. CONTRACT RENEGOTIATION AND COASIAN DYNAMICS. *Review of Economic Studies*, 55(4), 509-540.

Hong, Z., Li, M., Han, X., He, X., 2020. Innovative green product diffusion through word of mouth. *Transportation Research*

Part E-Logistics and Transportation Review, 134.
Huang, H., Meng, Q., Xu, H., Zhou, Y., 2019. Cost information sharing under competition in remanufacturing. *International Journal of Production Research*, 57(21), 6579-6592.
Inderst, R., Valletti, T., 2009. Price discrimination in input markets. *Rand Journal of Economics*, 40(1), 1-19.
Ingene, C. A., Parry, M. E., 1995. Channel coordination when retailers compete. *Marketing Science*, 14(4), 360-377.
Jin, Y., Hu, Q., Kim, S. W., Zhou, S. X., 2019. Supplier Development and Integration in Competitive Supply Chains. *Production and Operations Management*, 28(5), 1256-1271.
Jin, Y., Wu, X., Hu, Q., 2017. Interaction between channel strategy and store brand decisions. *European Journal of Operational Research*, 256(3), 911-923.
Katz, M. L., 1987. THE WELFARE EFFECTS OF 3RD-DEGREE PRICE-DISCRIMINATION IN INTERMEDIATE GOOD MARKETS. *American Economic Review*, 77(1), 154-167.
Kim, B., 2000. Coordinating an innovation in supply chain management. *European Journal of Operational Research*, 123(3), 568-584.
Li, G., Zhou, Y., 2016. Strategically decentralise when encroaching on a dominant supplier. *International Journal of Production Research*, 54(10), 2989-3005.
Li, X., Cui, X., Li, Y., Xu, D., Xu, F., 2021. Optimisation of reverse supply chain with used-product collection effort under collector's fairness concerns. *International Journal of Production Research*, 59(2), 652-663.
Li, Y., 2013. Timing of investments and third degree price discrimination in intermediate good markets. *Economics Letters*, 121(2), 316-320.
Lou, Y., He, Z., Feng, L., Cai, K., He, S., 2021. Original design manufacturer's warranty strategy when considering retailers' brand power under different power structures. *International Transactions in Operational Research*, 29, 1308-1325
Luchs, R., Geylani, T., Dukes, A., Srinivasan, K., 2010. The End of the Robinson-Patman Act? Evidence from Legal Case Data. *Management Science*, 56(12), 2123-2133.
Niu, B., Zeng, F., Chen, L., 2021. "Production plus procurement" outsourcing with competitive contract manufacturer's partial learning and supplier's price discrimination. *International Transactions in Operational Research*, 28(4), 1917-1951.
O'Brien, D. P., 2014. The welfare effects of third-degree price discrimination in intermediate good markets: the case of bargaining. *Rand Journal of Economics*,45(1), 92-115.
Plambeck, E. L., Taylor, T. A., 2005. Sell the plant? The impact of contract manufacturing on innovation, capacity, and profitability. *Management Science*, 51(1), 133-150.
Reimann, M., Xiong, Y., Zhou, Y., 2019. Managing a closed-loop supply chain with process innovation for remanufacturing. *Journal of the Operational Research Society*, 276(2), 510-518.
Roy, S., Sivakumar, K., 2010. Innovation generation in upstream and downstream business relationships.*Journal of Business Research*, 63(12), 1356-1363.
Roy, S., Sivakumar, K., Wilkinson, I. F., 2004. Innovation generation in supply chain relationships: A conceptual model and research propositions. *Journal of the Academy of Marketing Science*, 32(1), 61-79.
Sabri, Y., Micheli, G. J. L., Nuur, C., 2018. Exploring the impact of innovation implementation on supply chain configuration. *Journal of Engineering and Technology Management*, 49, 60-75
Stokey, N. L., 1979. INTERTEMPORAL PRICE-DISCRIMINATION. *Journal of Economics*, 93(3), 355-371.
Usta, M., Erhun, F., Hausman, W. H., 2014. Supply Licensing When the Manufacturer Strategically Commits to Invest in R&D. *Naval Research Logistics*, 61(4), 341-350.
Vakharia, A. J., Wang, L., 2014. Uniform vs. Retailer-Specific Pricing: Incentive Alignment to Enhance Supply Chain Efficiency. *Production and Operations Management*, 23(7), 1176-1182.
Vanderwerf, P. A., 1992. EXPLAINING DOWNSTREAM INNOVATION BY COMMODITY SUPPLIERS WITH EXPECTED INNOVATION BENEFIT. *Research Policy*, 21(4), 315-333.
Villas-Boas, S. B., 2009. An empirical investigation of the welfare effects of banning wholesale price discrimination. *Rand Journal of Economics*, 40(1), 20-46.
Wu, C.-H., Chen, C.-W., Hsieh, C.-C., 2012. Competitive pricing decisions in a two-echelon supply chain with horizontal and vertical competition. *International Journal of Production Economics*, 135(1), 265-274.
Wu, X., Niederhoff, J. A., 2014. Fairness in Selling to the Newsvendor. *Production and Operations Management*, 23(11), 2002-2022.
Wu, X., Zhou, Y., 2017. The optimal reverse channel choice under supply chain competition. *European Journal of Operational*

Research, 259(1), 63-66.
Wu, X., Zhou, Y., 2019. Buyer-specific versus uniform pricing in a closed-loop supply chain with third-party remanufacturing. *European Journal of Operational Research*, 273(2), 548-560.
Xu, H., Liu, X., Huang, H., Zhou, Y., Wei, Y., 2022. Innovation information sharing between two competitive supply chains. *International Transactions in Operational Research*,29(1), 471-495.
Yoshida, Y., 2000. Third-degree price discrimination in input markets: Output and welfare. *American Economic Review*, 90(1), 240-246.

Appendix A: Proofs

For ease of exposition, we define the following thresholds:

$$N_1 = \left(4-b^2\right)\left(\left(4-b^2\right)^2 I - 2\left({r_1}^2+{r_2}^2\right)\right)I + {r_1}^2{r_2}^2,$$

$$N_2 = \left(4-b^2\right)\left(\left(4-b^2\right)^2 I - 8\left({r_1}^2+{r_2}^2\right)\right)I + 16{r_1}^2{r_2}^2,$$

$$N_3 = 8\left(4-b^2\right)^3 I^2 - (6+b)^2\left(\left(4-b^2\right)\left({r_1}^2+{r_2}^2\right)I - {r_1}^2{r_2}^2\right).$$

Proof of sensitivity analysis

With the assumption $I > I_{\min}$, it is easy to obtain the impact of model parameters, a, c, r, and I. To save place, we present the sensitivity analysis on the parameter b only.

(1) $\frac{\partial \theta_i^{FB*}}{\partial b} = \frac{(a-2c)\begin{pmatrix} (2+b)^3(2-b)^4(3b-2)I^2 \\ +2\left(4-b^2\right)^2\left((1-b){r_j}^2+{r_i}^2\right)I \\ -\left(\left(4-3b^2\right){r_i}^2-4b{r_j}^2\right){r_j}^2 \end{pmatrix} I r_i}{2{N_1}^2}$, only if $b < \frac{2}{3}$ and $I > \frac{(2+b)((3b-1){r_j}^2-{r_i}^2)-((2+b)({r_i}^2-{r_j}^2)((2+b){r_i}^2-(9b^3-3b+2){r_j}^2))^{1/2}}{(3b-2)(4-b^2)^2}$, $\frac{\partial \theta_i^{FB*}}{\partial b} < 0$; otherwise, $\frac{\partial \theta_i^{FB*}}{\partial b} > 0$.

(2) $\frac{\partial \theta_i^{C*}}{\partial b} = \frac{(a-2c)\begin{pmatrix} (2+b)^3(2-b)^4(3b-2)I^2 \\ +8\left(4-b^2\right)^2\left((1-b){r_j}^2+{r_i}^2\right)I \\ -16\left(\left(4-3b^2\right){r_i}^2-4b{r_j}^2\right){r_j}^2 \end{pmatrix} I r_i}{2{N_2}^2}$, only if $b < \frac{2}{3}$ and $I > \frac{4(2+b)((3b-1){r_j}^2-{r_i}^2)-4((2+b)({r_i}^2-{r_j}^2)((2+b){r_i}^2-(9b^3-3b+2){r_j}^2))^{1/2}}{(3b-2)(4-b^2)^2}$, $\frac{\partial \theta_i^{C*}}{\partial b} < 0$; otherwise, $\frac{\partial \theta_i^{C*}}{\partial b} > 0$.

(3) $\frac{\partial \theta_i^{FU*}}{\partial b} = \frac{(a-2c)\begin{pmatrix} 16\left(4-b^2\right)^3\left(b^2+8b-4\right)(2-b)I^2 \\ -8\left(4-b^2\right)^2(6+b)\left(\left(2b^2+17b-2\right){r_j}^2-(6+b){r_i}^2\right)I \\ -(6+b)^2\left((6+b)^2 b{r_j}^2+\left(\left(3b^2+28b+12\right)b-32\right){r_i}^2\right){r_j}^2 \end{pmatrix} r_i I}{{N_3}^2}$, only if $b < 2\sqrt{5}-4$ and $I > \frac{\begin{pmatrix} (2+b)\left(\left(2b^2+17b-2\right){r_j}^2-(6+b){r_i}^2\right) \\ -\left((2+b)\left({r_i}^2-{r_j}^2\right)\begin{pmatrix} (2+b)(6+b)^2{r_i}^2 \\ -\left(3b^5+56b^4+289b^3+254b^2+12b+8\right){r_j}^2 \end{pmatrix}\right)^{1/2} \end{pmatrix}}{4(b^2+8b-4)(2-b^2)^2}$,

$\frac{\partial \theta_i^{FU*}}{\partial b} < 0$; otherwise, $\frac{\partial \theta_i^{FU*}}{\partial b} > 0$.

(4) $\frac{\partial E(w_i^{FB*})}{\partial b} = \frac{(a-2c)\left(\begin{array}{l}(2+b)^3(2-b)^4(3b-2)I^2\\ +2\left(4-b^2\right)^2\left((1-b)r_j{}^2+r_i{}^2\right)I\\ -\left(\left(4-3b^2\right)r_i{}^2-4br_j{}^2\right)r_j{}^2\end{array}\right)Ir_i{}^2}{4N_1{}^2}$, similarly, only if $b < \frac{2}{3}$ and $I > \frac{\left(\begin{array}{l}(2+b)\left((3b-1)r_j{}^2-r_i{}^2\right)\\ -\left((2+b)\left(r_i{}^2-r_j{}^2\right)\left((2+b)r_i{}^2-\left(9b^3-3b+2\right)r_j{}^2\right)\right)^{1/2}\end{array}\right)}{(3b-2)(4-b^2)^2}$, $\frac{\partial E(w_i^{FB*})}{\partial b} < 0$; otherwise, $\frac{\partial E(w_i^{FB*})}{\partial b} > 0$.

(5) $\frac{\partial E(w^{FU*})}{\partial b} = \frac{(2+b)(a-2c)\left(\begin{array}{l}\left(b^2+8b-4\right)\left(r_1{}^2+r_2{}^2\right)\\ \left(4\left(4-b^2\right)^2(2-b)^2I^2+r_1{}^2r_2{}^2(6+b)^2\right)\\ -2\left(2+b\right)\left(6+b\right)\left(2-b\right)^2\\ \left(\left(4b^2+34b-4\right)r_1{}^2r_2{}^2-(6+b)\left(r_1{}^4+r_2{}^4\right)\right)I\end{array}\right)I}{N_3{}^2}$, similarly, only if $b < 2\sqrt{5}-4$ and $I > \frac{(6+b)\left(\begin{array}{l}\left(2\left(2b^2+17b-2\right)r_1{}^2r_2{}^2-(6+b)\left(r_1{}^4+r_2{}^4\right)\right)\\ -\left(\left(r_1{}^2-r_2{}^2\right)^2\left(\begin{array}{l}\left(b^2+9b+2\right)^2r_1{}^2r_2{}^2\\ -(6+b)^2\left(r_1{}^2+r_2{}^2\right)^2\end{array}\right)\right)^{1/2}\end{array}\right)}{4(b^2+8b-4)(2+b)(2-b)^2(r_1{}^2+r_2{}^2)}$, $\frac{\partial E(w^{FU*})}{\partial b} < 0$; otherwise, $\frac{\partial E(w^{FU*})}{\partial b} > 0$.

Proof of equilibrium outcomes

(1) In the sub-game with flexible BSWP, at the final stage, $\pi_i^{FB} = \left(\frac{1}{2}(a+\varepsilon)+r_i\theta_i^{FB}-q_i^{FB}-bq_j^{FB}-w_i^{FB}-c\right)q_i^{FB}-\frac{1}{2}I\left(\theta_i^{FB}\right)^2$ is concave in q_1^{FB} and q_2^{FB}, respectively. From the first-order conditions, that is $\frac{\partial \pi_i^{FB}}{\partial q_i^{FB}} = \frac{1}{4}\left(a+\varepsilon-2c-2r_i\theta_i^{FB}-2bq_j^{FB}-2w_i^{FB}\right) = 0$. we have $q_i^{FB}\left(\theta_i^{FB},\theta_j^{FB},w_i^{FB},w_j^{FB}\right)$ in Equation (4). Then maximize the profit function of the supplier in Equation (5). The first partial derivatives of π_s^{FB} with respect to w_1^{FB} and w_2^{FB} are derived as follows: $\frac{\partial \pi_s^{FB}}{\partial q_i^{FB}} = \frac{(2-b)(a-2c+\varepsilon)+4r_i\theta_i^{FB}-2b\left(r_j\theta_j^{FB}-2w_j^{FB}\right)q_j^{FB}-8w_i^{FB}}{2(4-b^2)}$. The second partial derivatives of π_s^{FB} with respect to w_1^{FB} and w_2^{FB} are derived as follows: $\frac{\partial^2 \pi_s^{FB}}{\partial (q_1^{FB})^2} = -\frac{4}{4-b^2}$, $\frac{\partial^2 \pi_s^{FB}}{\partial (q_2^{FB})^2} = -\frac{4}{4-b^2}$, $\frac{\partial^2 \pi_s^{FB}}{\partial q_1^{FB}\partial q_2^{FB}} = \frac{2b}{4-b^2}$. The Hessian Matrix of π_s^{FB} is $H = \begin{pmatrix} -\frac{4}{4-b^2} & \frac{2b}{4-b^2} \\ \frac{2b}{4-b^2} & -\frac{4}{4-b^2}\end{pmatrix}$, then $|H| = \frac{4}{4-b^2} > 0$. Thus, the solution to the first order conditions gives the unique maximiser. Let $\frac{\partial \pi_s^{FB}}{\partial q_1^{FB}} = 0$ and $\frac{\partial \pi_s^{FB}}{\partial q_2^{FB}} = 0$, we have w_i^{FB} in Equation (6). At the first stage, buyer i maximize expected profit $E\left(\pi_i^{FB}\left(\theta_i^{FB}\right)\right)$ in Equation (7). From the first-order conditions, that is $\frac{\partial E(\pi_i^{FB}(\theta_i^{FB}))}{\partial \theta_i^{FB}} = \frac{\left((2-b)(a-2c)-2br_j\theta_j^{FB}\right)r_i}{2(4-b^2)I-4r_i} = 0$, we have θ_i^{FB*} in Equations (8). Then Substituting θ_i^{FB*} back into Equation (6), we obtain $E\left[w_i^{FB*}\right] = \frac{a}{4}+\frac{r_i\theta_i^{FB*}}{2}-\frac{c}{2} =$

$\frac{\left((4-b^2)^2 I - b{r_i}^2 - 2{r_j}^2\right)(a-2c)(4-b^2)I}{4(4-b^2)\left((4-b^2)^2 I - 2({r_i}^2+{r_j}^2)\right)I + 4{r_i}^2{r_j}^2}$, then substituting θ_i^{FB*} and $E\left[w_i^{FB*}\right]$ into and Equation (4), $E\left[q_i^{FB*}\right] = \frac{(2-b)(a-2c)+4r_i\theta_i^{FB*}-2br_j\theta_j^{FB*}-4E[w_i^{FB*}]+2bE\left[w_j^{FB*}\right]}{2(4-b^2)} = \frac{\left((2-b)^2(2+b)I-{r_j}^2\right)(a-2c)(4-b^2)I}{4(4-b^2)\left((4-b^2)^2 I-2({r_i}^2+{r_j}^2)\right)I+4{r_i}^2{r_j}^2}$. Substituting θ_i^{FB*} and w_i^{FB*} back into Equation (5) and integrating over ε give the expected optimal profits of the supplier:

$$E\left[\pi_s^{FB}\right] = \frac{(a-2c)^2(4-b^2)^2\begin{pmatrix}\left(4-b^2\right)^2\left((2+b)(2-b)^2 I-\left({r_1}^2+{r_2}^2\right)\right)I\\ +b{r_1}^2{r_2}^2+{r_1}^4+{r_2}^4\end{pmatrix}I^2}{8{N_1}^2}+\frac{\sigma^2}{8(2+b)}.$$

Substituting Equations (4) and (6) into Equation (3), we have $\pi_i^{FB}\left(\theta_i^{FB}\right) = \left(\frac{1}{2}(a+\varepsilon)-q_i^{FB}-bq_j^{FB}-c-w_i^{FB}-r_i\theta_i^{FB}\right) - \frac{1}{2}I\left(\theta_i^{FB}\right)^2$, then we integrate over ε, $E\left(\pi_i^{FB}\left(\theta_i^{FB}\right)\right)$ in Equation (7) are obtained. Substituting θ_i^{FB*} back into Equations (10) and (11) gives the expected optimal profits of supplier i:

$$E\left[\pi_i^{FB}\right] = \frac{(a-2c)^2\left((2+b)(2-b)^2 I-{r_j}^2\right)^2\left(\left(4-b^2\right)^2 I-2{r_i}^2\right)I}{16{N_1}^2}+\frac{\sigma^2}{16(2+b)^2}.$$

(2) In the sub-game with flexible UWP, at the final stage, consistent with the sub-game of flexible B-SWP, from the first-order conditions of $\pi_i^{FU} = \left(\frac{1}{2}(a+\varepsilon)+r_i\theta_i^{FU}-q_i^{FU}-bq_j^{FU}-w^{FU}-c\right)q_i^{FU} - \frac{1}{2}I\left(\theta_i^{FU}\right)^2$, that is $\frac{\partial\pi_i^{FU}}{\partial q_i^{FU}} = \frac{1}{4}\left(a+\varepsilon-2c-2r_i\theta_i^{FU}-2bq_j^{FU}-2w^{FU}\right) = 0$, we have $q_i^{FU}\left(\theta_i^{FU},\theta_j^{FU},w^{FU}\right)$ in Equation (9). Then maximize the suppliers profit function $\pi_s^{FU}\left(\varepsilon,\theta_1^{FU},\theta_2^{FU};w^{FU}\right)$ in Equation (10). From the first-order conditions, that is $\frac{\partial\pi_s^{FU}}{\partial w^{FU}} = \frac{a+\varepsilon-2c+r_1\theta_1^{FU}+r_2\theta_2^{FU}-4w^{FU}}{(2+b)} = 0$, we have w^{FU} in Equation (11). Then in the first stage, buyer i decides θ_i^{FU} to maximize expected profit $E\left(\pi_i^{FU}\left(\theta_i^{FU}\right)\right)$ in Equation (12), from the first-order conditions, that is $\frac{\partial E(\pi_i^{FU}(\theta_i^{FU}))}{\partial\theta_i^{FU}} = \frac{\left((6+b)^2{r_i}^2-8(4-b^2)^2 I\right)\theta_i^{FU}+(6+b)\left((2+b)(a-2c)r_i-(2+3b)r_ir_j\theta_j^{FU}\right)}{8(4-b^2)^2} = 0$, we have θ_i^{FU*} in Equations (13). Then substituting θ_i^{FU*} back into Equation (11), we obtain $E\left[w^{FU*}\right] = \frac{a}{4}-\frac{c}{2}+\frac{r_1\theta_1^{FU*}+r_2\theta_2^{FU*}}{4}+\frac{\varepsilon}{4} = \frac{\left(4(2+b)(2-b)^2 I-(6+b)({r_i}^2+{r_j}^2)\right)(a-2c)(2-b)(2+b)^2 I}{16(4-b^2)^3 I^2-2((4-b^2)({r_i}^2+{r_j}^2)I-{r_i}^2{r_j}^2)(6+b)^2}$, then substituting θ_i^{FU*} and $E\left[w^{FU*}\right]$ into and Equation (9), $E\left[q_i^{FU*}\right] = \frac{\left(2(2+b)(2-b)^2 I-(6+b){r_j}^2\right)(a-2c)(4-b^2)I}{8(4-b^2)^3 I^2-((4-b^2)({r_i}^2+{r_j}^2)I-{r_i}^2{r_j}^2)(6+b)^2}$. Substituting θ_i^{FU*} and w^{FU*} back into Equation (10) and integrating over ε give the expected optimal profits of the supplier:

$$E\left[\pi_s^{FU}\right] = \frac{2(a-2c)^2(2+b)^3(2-b)^2\begin{pmatrix}4(2+b)(2-b)^2 I\\ -(6+b)\left({r_1}^2+{r_2}^2\right)\end{pmatrix}I^2}{{N_3}^2}+\frac{\sigma^2}{8(2+b)}.$$

Substituting θ_i^{FU*} back into Equation (12) gives the expected optimal profits of the supplier i:

$$E\left[\pi_i^{FU}\right] = \frac{2(a-2c)^2\left(4-b^2\right)^2\left(2\left(2+b\right)\left(2-b\right)^2 I-\left(6+b\right)r_j{}^2\right)^2 I^2}{{N_2}^2} + \frac{\sigma^2}{16(2+b)^2}.$$

(3) In the sub-game with committed BSWP(UWP), at the final stage, consistent with the sub-game of flexible BSWP, we have $q_i^C\left(\theta_i^C,\theta_j^C,w_i^C,w_j^C\right) = \frac{(2-b)(a-2c+\varepsilon)+4r_i\theta_i^C-2br_j\theta_j^C-4w_i^C+2bw_j^C}{2(4-b^2)}$. Then maximize each buyers expected profit $E\left(\pi_i^C\left(w_1^C,w_2^C;\theta_i^C\right)\right)$ in Equations (14), from the first-order condition, that is $\frac{\partial E(\pi_i^C)}{\partial \theta_i^C} = \frac{2\left((2-b)(a-2c)-2br_j\theta_j^C-4w_i^C+2bw_j^C\right)r_i}{(4-b^2)I-8r_i{}^2} = 0$, we have $\theta_i^C\left(w_i^C,w_j^C\right)$ in Equations (15). Then in the first stage, maximize the supplier's expected profit $E\left(\pi_s^C\left(w_1^C,w_2^C\right)\right)$ in Equation (16). The first partial derivatives of $E\left(\pi_s^C\right)$ with respect to w_1^C and w_2^C are derived as follows: $\frac{\partial E(\pi_s^C)}{\partial w_i^C} = \frac{(4-b^2)((4-b^2)((a-2c)(2-b)-8w_1^C+4bw_2^C)I-4r_2{}^2(a-2c-4w_1^C))I}{2(4-b^2)\left((4-b^2)^2I-8(r_1{}^2+r_2{}^2)\right)I+32r_1{}^2r_2{}^2}$. The second partial derivatives of $E\left(\pi_s^C\right)$ with respect to w_1^C and w_2^C are derived as follows: $\frac{\partial^2\pi_s^C}{\partial (w_1^C)^2} = \frac{(4-b^2)(8r_2{}^2-4(4-b^2)I)I}{(4-b^2)\left((4-b^2)^2I-8(r_1{}^2+r_2{}^2)\right)I+16r_1{}^2r_2{}^2}$, $\frac{\partial^2\pi_s^C}{\partial (w_2^C)^2} = \frac{(4-b^2)(8r_1{}^2-4(4-b^2)I)I}{(4-b^2)\left((4-b^2)^2I-8(r_1{}^2+r_2{}^2)\right)I+16r_1{}^2r_2{}^2}$, $\frac{\partial^2\pi_s^C}{\partial w_1^C\partial w_2^C} = \frac{2b(4-b^2)^2I^2}{(4-b^2)\left((4-b^2)^2I-8(r_1{}^2+r_2{}^2)\right)I+16r_1{}^2r_2{}^2}$. Then with the assumption $I > I_{\min}$, the determinant of the Hessian can be written as: $|H| = \frac{\partial^2\pi_s^C}{\partial (w_1^C)^2}\frac{\partial^2\pi_s^C}{\partial (w_2^C)^2} - \left(\frac{\partial^2\pi_s^C}{\partial w_1^C\partial w_2^C}\right)^2 = \frac{2(4-b^2)^2I^2}{(4-b^2)\left((4-b^2)^2I-8(r_1{}^2+r_2{}^2)\right)I+16r_1{}^2r_2{}^2} > 0$, Thus, the solution to the first order conditions gives the unique maximizer. Let $\frac{\partial E(\pi_s^C)}{\partial w_1^C} = 0$ and $\frac{\partial E(\pi_s^C)}{\partial w_2^C} = 0$, we have w_i^{C*} in Equations (17). Then substituting w_i^{C*} back into Equation (15), we obtain $\theta_i^{C*} = \frac{2r_i((4-b^2)(2a+2bc-ab-4c-(4+2b)w_i^{C*})I-4r_j{}^2(a-2c-2w_i^{C*}))}{2(4-b^2)\left((4-b^2)^2I-8(r_i{}^2+r_j{}^2)\right)I+16r_i{}^2r_j{}^2} = \frac{(a-2c)\left((2+b)(2-b)^2I-4r_j{}^2\right)r_i}{(4-b^2)\left((4-b^2)^2I-8(r_i{}^2+r_j{}^2)\right)I+16r_i{}^2r_j{}^2}$. Substituting w_i^{C*} and θ_i^{C*} back into $q_i^C\left(\theta_i^C,\theta_j^C,w_i^C,w_j^C\right)$, we have $E\left[q_i^{C*}\right] = \frac{(2-b)(a-2c)+4r_i\theta_i^{C*}-2br_j\theta_j^{C*}-4E[w_i^{C*}]+2bE\left[w_j^{C*}\right]}{2(4-b^2)} = \frac{\left((2+b)(2-b)^2I-4r_j{}^2\right)(a-2c)(4-b^2)I}{4(4-b^2)\left((4-b^2)^2I-8(r_i{}^2+r_j{}^2)\right)I+64r_i{}^2r_j{}^2}$. Substituting w_i^{C*} back into Equations (16) gives the expected optimal profits of the supplier:

$$E\left[\pi_s^C\right] = \frac{(a-2c)^2\left(4-b^2\right)\left(\left(2+b\right)\left(2-b\right)^2 I-2\left({r_1}^2+{r_2}^2\right)\right)I}{8N_2}.$$

Substituting w_i^{C*} and θ_i^{C*}back into Equation (14) gives the expected optimal profits of supplier i:

$$E\left[\pi_i^C\right] = \frac{(a-2c)^2\left(\left(2+b\right)\left(2-b\right)^2 I-4r_j{}^2\right)^2\left(\left(4-b^2\right)^2 I-8r_i{}^2\right)I}{16{N_2}^2} + \frac{\sigma^2}{4(2+b)^2}.$$

All process innovation levels, wholesale prices and order quantities in equilibrium are summarized in Table 1.

Proof of Proposition 1

Let's denote $\Delta_{s1} = E\left[\pi_s^C\right] - E\left[\pi_s^{FU}\right]$, we have

$$\Delta_{s1} = \frac{(a-2c)^2\left(4-b^2\right) I \mathrm{H}_1}{8 N_2 {N_3}^2} - \frac{\sigma^2}{8\left(2+b\right)}. \tag{D1}$$

Here $\begin{array}{l} \mathrm{H}_1 = \left((2-b)^2\left(2+b\right)I - 2\left({r_1}^2 + {r_2}^2\right)\right){N_3}^3 \\ -4(2+b)^2\left(2-b\right)\left(4(2-b)^2\left(2+b\right)I - \left(6+b\right)\left({r_1}^2+{r_2}^2\right)\right)^2 I N_2 \end{array}$. With the assumption $I > I_{\min}$, $\mathrm{H}_1 > 0$. Thus, if $\sigma^2 \leq \mathrm{T}$, $E\left[\pi_s^C\right] \geq E\left[\pi_s^{FU}\right]$; if $\sigma^2 > \mathrm{T}$, $E\left[\pi_s^C\right] < E\left[\pi_s^{FU}\right]$. Here, $\mathrm{T} = \frac{(a-2c)^2(2+b)(4-b^2)I\mathrm{H}_1}{N_2{N_3}^2}$.

Denote $\Delta_{s2} = E\left[\pi_s^{FU}\right] - E\left[\pi_s^{FB}\right]$, we have

$$\Delta_{s2} = \frac{(a-2c)^2\left(4-b^2\right)^2 I^2 \mathrm{H}_2}{8{N_3}^2{N_1}^2}. \tag{D2}$$

Here $\begin{array}{l} \mathrm{H}_2 = 4\left(2+b\right)\left(4(2-b)^2\left(2+b\right)I - \left(6+b\right)\left({r_1}^2+{r_2}^2\right)\right)^2{N_1}^2 \\ -\left(\left(4-b^2\right)^2\left((2-b)^2\left(2+b\right)I - \left({r_1}^2+{r_2}^2\right)\right)I + b{r_1}^2{r_2}^2 + {r_1}^4 + {r_2}^4\right){N_3}^2 \end{array}$. Note that $N_1 - N_3$ is concave in I. It has an axis of symmetry $I = -\frac{\left(2+(6+b)^2\right)\left({r_1}^2+{r_2}^2\right)}{14(4-b^2)^2} < 0$, and $\left(N_1 - N_3\right)\big|_{I=I_{n2}^C} = -\frac{{r_1}^2\left((6+b)(37-b^2){r_2}^2+(4b^2+160b-376)\right)}{2-b} < 0$. With the assumption $I > \max\left\{I_{n2}^C, I_N^C\right\} = I_{\min}$, it is easy to obtain $N_1 > N_3 > 0$, then ${N_1}^2 > {N_3}^2$. Next, let $N_3 = N_1$ in H_2, we have $H_2 > H_2\left(N_3 = N_1\right) = D_1{N_1}^2$, where $\begin{array}{l} D_1 = 63(2+b)^3(2-b)^4 I^2 - \left(4-b^2\right)^2\left(191+32b\right)\left({r_1}^2+{r_2}^2\right)I \\ +4\left({r_1}^2+{r_2}^2\right)^2\left(14+b\right)b^2 + \left(240b+287\right)\left({r_1}^4+{r_2}^4\right) + \left(479b+576\right){r_1}^2{r_2}^2 \end{array}$, a convex function in I. It has an axis of symmetry $I = \frac{(191+32b)\left({r_1}^2+{r_2}^2\right)}{126(2-b)^2(2+b)} < I_{n2}^C$. Then if $I > I_{\min}$, $D_1 > 0$. Thus, we have ${N_1}^2 > {N_3}^2$ and $D_1 > 0$, then $E\left[\pi_s^{FU}\right] > E\left[\pi_s^{FB}\right]$.

Proof of Proposition 2

We have $E\left[\pi_1^C\right] - E\left[\pi_1^{FU}\right] = \frac{(a-2c)^2 M_1 I}{16{N_2}^2{N_3}^2} + \frac{3\sigma^2}{16(2+b)^2} > 0$, here $\begin{array}{l} M_1 = \left((2-b)^2\left(2+b\right)I - 4{r_2}^2\right)^2\left(\left(4-b^2\right)^2 I - 8{r_1}^2\right){N_3}^2 \\ -\left(4-b^2\right)^2\left(8(2-b)^2\left(2+b\right)I - 4\left(6+b\right){r_2}^2\right)^2 I {N_2}^2 \end{array}$. With the assumption

$$M\left(I_{\min} \geq I_{n2}^{C}\right) = \frac{64{r_1}^6({r_1}^2-{r_2}^2)^2 b\begin{pmatrix} {r_2}^4 b^6 + 4\left(2{r_1}^2 + 7{r_2}^2\right){r_2}^2 b^5 \\ +4\left(4{r_1}^4 - 12{r_1}^2{r_2}^2 + 15{r_2}^4\right)b^4 \\ -16\left(20{r_1}^4 - 66{r_1}^2{r_2}^2 + 55{r_2}^4\right)b^3 \\ -16\left(608{r_1}^4 - 1288{r_1}^2{r_2}^2 + 609{r_2}^4\right)b^2 \\ -64\left(232{r_1}^4 - 378{r_1}^2{r_2}^2 + 153{r_2}^4\right)b \\ +64\left(14{r_1}^2 - 9{r_2}^2\right)^2 \end{pmatrix}}{(2-b)^2} > 0.$$ Thus, $E\left[\pi_1^C\right] - E\left[\pi_1^{FU}\right] > 0$.

We have $E\left[\pi_1^{FU}\right] - E\left[\pi_1^{FB}\right] = \frac{(a-2c)^2 M_2 I}{16{N_1}^2{N_3}^2}$, here

$$\begin{array}{l} M_2 = \left(4-b^2\right)^2\left(8(2-b)^2(2+b)I - 4(6+b){r_2}^2\right)^2 I{N_1}^2 \\ -\left((2-b)^2(2+b)I - {r_2}^2\right)^2\left(\left(4-b^2\right)^2 I - 2{r_1}^2\right){N_3}^2 \end{array}.$$

Because ${N_1}^2 > {N_3}^2$, we have $M_2 > M_2(N_3 = N_1) = D_2{N_1}^2$, where $\begin{array}{l} D_2 = 63(2+b)^4(2-b)^6 I^3 - 2(2+b)^2(2-b)^4\left((191+32b)(2+b){r_2}^2 - {r_1}^2\right)I^2 \\ +(2+b)(2-b)^2\left((25+4b)(23+4b)(2+b){r_2}^2 - 4{r_1}^2\right)^2 I + 2{r_1}^2{r_2}^4 \end{array}$. $\partial D_2/\partial I$ is a convex function in I. It has an axis of symmetry $I = \frac{2\left((32b^2+255b+382){r_2}^2 - {r_1}^2\right)}{189(4-b^2)^2} < I_{n2}^C$ and $\frac{\delta D_2}{\delta I}\Big|_{I=I_{n2}^C} = (2+b)(2-b)^2\begin{pmatrix} (25+4b)(23+4b)(2+b){r_2}^4 - \left(512b^2 + 4080b - 6116\right){r_1}^2{r_2}^2 \\ +(3024b + 60642){r_1}^4 \end{pmatrix} > 0$

Then with the assumption $I > I_{\min} \geq I_{n2}^C$, $\partial D_2/\partial I > 0$. $D_2\left(I_{\min} \geq I_{n2}^C\right) = \begin{pmatrix} (8096 + 4032b){r_1}^4 + \left(64b^3 + 896b^2 + 3836b + 4602\right){r_2}^4 \\ +16\left(64b^2 + 510b + 765\right){r_1}^2{r_2}^2 \end{pmatrix}{r_1}^2 > 0$. Thus, we have $M_2 > D_2{N_1}^2 > 0$, then $E\left[\pi_1^{FU}\right] - E\left[\pi_1^{FB}\right] > 0$.

Therefore, the committed UWP strategy is always preferred by Buyer 1. However, when the supplier chooses the flexible UPW strategy, Buyer 1 still obtains a greater profit compared with the flexible BSWP strategy. Therefore, we say that the UPW strategy is beneficial to Buyer 1.

Proof of Proposition 3

Let's denote $\Delta_{21} = E\left[\pi_2^C\right] - E\left[\pi_2^{FB}\right]$, we have

$$\Delta_{21} = \frac{(a-2c)^2 M_3 I}{16{N_1}^2{N_2}^2} + \frac{3\sigma^2}{16(2+b)^2}. \tag{F1}$$

Here $\begin{array}{l} M_3 = \left(\left(4-b^2\right)^2 I - 8{r_2}^2\right)\left((2+b)(2-b)^2 I - 4{r_1}^2\right)^2{N_1}^2 \\ -\left(\left(4-b^2\right)^2 I - 2{r_2}^2\right)\left((2+b)(2-b)^2 I - {r_1}^2\right)^2{N_2}^2 \end{array}$. We have $\partial\Delta_{21}/\partial\left(\sigma^2\right) > 0$. Thus, the committed UWP is preferred over the flexible BSWP by Buyer 2 if σ^2 is big enough. However, the committed pricing will be adopted by the supplier only if σ^2 is small. Given $\sigma^2 = \mathrm{T}$, with the assumption $I > I_{\min}$, if ${r_2}^2 < b{r_1}^2$, $\partial\Delta_{21}/\partial I < 0$ and $\Delta_{21}\left(I_{\min} \geq I_{n2}^C\right) < 0$. That is to say, the flexible BSWP is preferred over the committed UWP.

Next, denote $\Delta_{22} = E\left[\pi_2^{FB}\right] - E\left[\pi_2^{FU}\right]$, we have

$$\Delta_{22} = \frac{(a-2c)^2 M_4 I}{16{N_1}^2{N_3}^2}. \tag{F2}$$

Here $\begin{array}{l} M_4 = \left((4-b^2)^2 I - 2{r_2}^2\right)\left((2+b)(2-b)^2 I - {r_1}^2\right)^2 {N_3}^2 \\ -16(4-b^2)^2\left((2+b)(2-b)^2 I - (6+b){r_1}^2\right)^2 I{N_1}^2 \end{array}.$

Because ${N_1}^2 > {N_3}^2$, $M_4 < M_4(N_1 = N_3) = D_3{N_3}^2 > 0$, where $\begin{array}{l} D_3 = -63(2+b)^4(2-b)^6 I^3 + 2(2+b)^2(2-b)^4\left((191+32b)(2+b){r_1}^2 - {r_2}^2\right)I^2 \\ +(2+b)(2-b)^2\left((25+4b)(23+4b)(2+b){r_1}^2 - 4{r_2}^2\right)^2 I + 2{r_1}^4{r_2}^2 \end{array}.$

Then with the assumption $I > I_{\min}$, $\partial M_4/\partial I > 0$ and $M_4\left(I_{\min} \geq I_{n2}^C\right) = \frac{{r_1}^{10}(a-2c)^2\left(\begin{array}{l} 9\left({r_2}^2 - 2(2+b){r_1}^2\right)\left(\left(4b^2+176b+400\right){r_1}^2 + (6+b)^2(6-b){r_2}^2\right)^2 \\ +32{r_1}^2\left(8(3+2b){r_1}^2 + (6+b){r_2}^2\right)^2(2+b)(2-b)^2 \end{array}\right)}{2(2+b)(2-b)^4} > 0.$

Thus, $\Delta_{22} > 0$, that is to say, the flexible BSWP is preferred over the flexible UWP by Buyer 2.

Appendix B: Constraints on parameters

Note that the wholesale prices in the case of committed BSWP(UWP) must be positive, i.e., $w_i^{C*} = \frac{a-2c}{4} > 0$, so we obtain $c \leq a/2$.

In order to obtain optimal process innovation level in the basic model is always great than 0 and less than 1, we analyze θ_i^* in three scenarios. Here, we use the subscript $d(n)$ denote the roots when the denominator (numerator) equals zero.

First, note that $\theta_i^{FB*} = \frac{(a-2c)\left((2+b)(2-b)^2 I - {r_j}^2\right)r_i}{2N_1}$. The denominator $2N_1$ is convex in I. Equate $2N_1$ to zero, and solve for I. We obtain when $\underline{I}_d^{FB} = \frac{r_1^2+r_2^2-\sqrt{b^2r_1^2r_2^2+(r_1^2-r_2^2)^2}}{(4-b^2)^2} < I < \overline{I}_d^{FB} = \frac{r_1^2+r_2^2+\sqrt{b^2r_1^2r_2^2+(r_1^2-r_2^2)^2}}{(4-b^2)^2}$, $2N_1 < 0$, otherwise, $2N_1 > 0$. Then equate the numerator of θ_i^{FB*} to zero, i.e., $(a-2c)\left((2+b)(2-b)^2 I - {r_j}^2\right)r_i = 0$. We have $I_{ni}^{FB} = \frac{{r_j}^2}{(2+b)(2-b)^2}$, and $I_{n1}^{FB} < I_{n2}^{FB}$. Because $\underline{I}_d^{FB} - I_{n_1}^{FB} = \frac{r_1^2-(1+b)r_2^2-\sqrt{b^2r_1^2r_2^2+(r_1^2-r_2^2)^2}}{2+b} < 0$, $\overline{I}_d^{FB} - I_{n_1}^{FB} = \frac{r_1^2+\sqrt{(r_1^2-r_2^2)^2+b^2r_1^2r_2^2}-(1+b)r_2^2}{2+b} > 0$ and $\overline{I}_d^{FB} - I_{n_2}^{FB} = \frac{r_2^2+\sqrt{(r_1^2-r_2^2)^2+b^2r_1^2r_2^2}-(1+b)r_1^2}{2+b} < 0$. It is easy to obtain $\underline{I}_d^{FB} < I_{n1}^{FB} < \overline{I}_d^{FB} < I_{n2}^{FB}$. Therefore, only if $\underline{I}_d^{FB} < I < I_{n1}^{FB}$ or $I > I_{n2}^{FB}$, $\theta_i^{FB*} > 0$.

Next, from $\theta_i^{FB*} < 1$, we obtain

$$K_i = \frac{\left(\begin{array}{l} (4-b^2)\left(2(4-b^2)^2 I - (2-b)(a-2c)r_i - 4\left({r_i}^2 + {r_j}^2\right)\right)I \\ +(a-2c+2r_i)r_i{r_j}^2 \end{array}\right)}{2N_1} > 0.$$

$\frac{\partial K_1}{\partial I} = -\frac{(a-2c)(4-b^2)\left((4-b^2)^2((2-b)(4-b^2)I-2{r_2}^2)I+b{r_1}^2{r_2}^2+2{r_2}^4\right)r_1}{2N_1^2}$. Because

$(4-b^2)^2\left((2-b)\left(4-b^2\right)I-2{r_2}^2\right)I+b{r_1}^2{r_2}^2+2{r_2}^4$ is convex in I, and $\Delta = -b\,(2-b)\left({r_1}^2-{r_2}^2\right) < 0$, $\partial K_1/\partial I < 0$. Let $K_1 = 0$, $I = \frac{\left(\begin{array}{l}\left(8\,(a-2c+r_1)\,r^2+(a-2c)^2 r_1\right)b^2 r_1\\ -4\,(a-2c)\left((a-2c)\,{r_1}^2+2\left({r_1}^2+{r_2}^2\right)\right)b\\ +4\left((a-2c)\,{r_1}^2+2\left({r_1}^2-{r_2}^2\right)\right)^2\end{array}\right)^{1/2}}{4(4-b^2)^2} + \frac{(a-2c)(2-b){r_1}^2+4({r_1}^2+{r_2}^2)}{4(4-b^2)^2} = I_N^{FB}$, only if $I > I_N^{FB}$, $\theta_i^{FB*} < 1$.

Finally, combine the above conditions, because of $I_N^{FB} > I_{n1}^{FB}$, only if $I > \max\left\{I_{n2}^{FB}, I_N^{FB}\right\}$, $0 < \theta_i^{FB*} < 1$.

Similar to the proof of $\theta_i^{FB*} > 0$. Because $\theta_i^{C*} = \frac{(a-2c)\left((2+b)(2-b)^2 I-4{r_j}^2\right)r_i}{N_2}$, the denominator N_2 is convex in I, then when $\underline{I}_d^C = \frac{4(r_1^2+r_2^2-\sqrt{b^2r_1^2r_2^2+(r_1^2-r_2^2)^2})}{(-b^2+4)^2} < I < \overline{I}_d^C = \frac{4(r_1^2+r_2^2-\sqrt{b^2r_1^2r_2^2+(r_1^2-r_2^2)^2})}{(-b^2+4)^2}$, $N_2 < 0$, otherwise, $N_2 > 0$. And if $I > I_{n2}^C = \frac{4{r_1}^2}{(2+b)(2-b)^2}$, the numerator, i.e., $(a-2c)\left((2+b)\,(2-b)^2 I-4{r_j}^2\right)r_i > 0$. Therefore, only if $\underline{I}_d^C < I < I_{n1}^C$ or $I > I_{n2}^C$, $\theta_i^{C*} > 0$.

Then from $\theta_i^{C*} < 1$, we obtain only if $I > \frac{\left(\begin{array}{l}\left((a-2c)^2(2-b)^2-64\left(2-b^2\right){r_2}^2\right){r_1}^2\\ +16\,(2-b)\,(a-2c)\left({r_1}^2-(1+b)\,{r_2}^2\right)r_1\\ +64\left({r_1}^4+{r_2}^4\right)^2\end{array}\right)^{1/2}}{2(4-b^2)^2} + \frac{(a-2c)(2-b){r_1}^2+8({r_1}^2+{r_2}^2)}{2(4-b^2)^2} = I_N^C$, $\theta_i^{C*} < 1$. Because of $I_N^C > I_{n1}^C$, only if $I > \max\left\{I_{n2}^C, I_N^C\right\}$, $0 < \theta_i^{C*} < 1$.

Similarly, only if $\underline{I}_d^{FU} < I < I_{n1}^{FU}$ or $I > I_{n2}^{FU}$, $\theta_i^{FU*} > 0$, where $I_{n2}^{FU} = \frac{(6+b){r_1}^2}{2(2+b)(2-b)^2}$. Then from $\theta_i^{FU*} < 1$, we obtain only if $I > \frac{(6+b)\left(\begin{array}{l}\left(\begin{array}{l}(a-2c)^2(2-b)^2\\ -2\left(28-17b^2\right){r_2}^2\end{array}\right){r_1}^2\\ +2\,(2-b)\,(a-2c)\left((6+b)\,{r_1}^2-(10+7b)\,{r_2}^2\right)r_1\\ +(6+b)^2\left({r_1}^4+{r_2}^4\right)^2\end{array}\right)^{1/2}}{16(4-b^2)^2} + \frac{(6+b)\left(\begin{array}{l}(a-2c)\,(2-b)\,{r_1}^2\\ +(6+b)\left({r_1}^2+{r_2}^2\right)\end{array}\right)}{16(4-b^2)^2} = I_N^{FU}$, $\theta_i^{FU*} < 1$. Because of $I_N^{FU} > I_{n1}^{FU}$, only if $I > \max\left\{I_{n2}^{FU}, I_N^{FU}\right\}$, $0 < \theta_i^{FU*} < 1$.

Note that $I_{n2}^{FB} < I_{n2}^{FU} < I_{n2}^C$. If $I > I_{n2}^C$, we have $I_N^{FB} < I_N^{FU} < I_N^C$. Thus, only if $I > \max\left\{I_{n2}^C, I_N^C\right\} = I_{\min}$, $0 < \theta_i^* < 1$.

Recall that $0 < r_2 \le r_1 < c$. Because when $I > I_{\min}$, $\theta_i^* > 0$, $N_1 > 0$, $N_2 > 0$, and $N_3 > 0$. Then from $\theta_i^{FB*} = \frac{(a-2c)\left((2+b)(2-b)^2 I-{r_j}^2\right)r_i}{2N_1}$, we have $(2+b)\,(2-b)^2 I-{r_1}^2 > 0$. Then $E\left[q_i^{FB*}\right] = \frac{(a-2c)\left((2+b)(2-b)^2 I-{r_1}^2\right)r_2}{4N_1} > 0$, and $E\left[w_i^{FB*}\right] = \frac{\left((4-b^2)^2 I-b{r_i}^2-2{r_j}^2\right)(a-2c)(4-b^2)I}{4N_1} >

$\frac{\left((2+b)(2-b)^2 I - {r_1}^2\right)(a-2c)(4-b^2)I}{4N_1} > 0$. Because $\theta_i^{FU*} = \frac{\left(2(2+b)(2-b)^2 I - (6+b){r_j}^2\right)(a-2c)(6+b)r}{2N_3} > 0$, $2\left(2+b\right)\left(2-b\right)^2 I - \left(6+b\right){r_1}^2 > 0$. Then $E\left[q_i^{FU*}\right] = \frac{\left(2(2+b)(2-b)^2 I - (6+b){r_j}^2\right)(a-2c)(4-b^2)I}{N_3} > 0$, and $E\left[w_i^{FU*}\right] = \frac{\left(4(2+b)(2-b)^2 I - (6+b)({r_i}^2+{r_j}^2)\right)(a-2c)(2-b)(2+b)^2 I}{2N_3} > \frac{2\left(2(2+b)(2-b)^2 I - (6+b){r_1}^2\right)(a-2c)(2-b)(2+b)^2 I}{2N_3} > 0$. Because $I > I_{n2}^C = \frac{4{r_1}^2}{(2+b)(2-b)^2} \geq \frac{4{r_j}^2}{(2+b)(2-b)^2}$, $E\left[w^{C*}\right] = \frac{(a-2c)\left((2+b)(2-b)^2 I - 4{r_j}^2\right)r_i}{N_2} > 0$ and $E\left[q_i^{C*}\right] = \frac{\left((2+b)(2-b)^2 I - 4{r_j}^2\right)(a-2c)(4-b^2)I}{4N_2} > 0$. Thus, all constraints on parameters make equilibrium solutions be positive.

Appendix C: Impacts of different parameters

We choose parameters a, c, b, r_1 and r_2 to discuss the supplier's preference over price commitment and flexible pricing strategy in Proposition 1. Because H_1, N_2 and N_3 are all independent of a and c, we have if the unite cost is low enough, i.e., $c \leq \frac{1}{2}\left(a - N_3\sqrt{\frac{\sigma^2 N_2}{(4-b^2)I\mathrm{H}_1}}\right)$, the supplier prefers a committed pricing strategy, i.e., $E\left[\pi_s^C\right] \geq E\left[\pi_s^{FU}\right] > E\left[\pi_s^{FB}\right]$; otherwise, the supplier prefers a flexible UWP strategy, i.e., $E\left[\pi_s^{FU}\right] > \max\left\{E\left[\pi_s^C\right], E\left[\pi_s^{FB}\right]\right\}$. And if the market size is large enough, i.e., $a \geq 2c + N_3\sqrt{\frac{\sigma^2 N_2}{(4-b^2)I\mathrm{H}_1}}$, $E\left[\pi_s^C\right] \geq E\left[\pi_s^{FU}\right] > E\left[\pi_s^{FB}\right]$, otherwise $E\left[\pi_s^{FU}\right] > \max\left\{E\left[\pi_s^C\right], E\left[\pi_s^{FB}\right]\right\}$. Let $\sigma^2 = \frac{1}{200}$, $I = 1$, $a = 1$, $c = \frac{1}{4}$, $r_1 = \frac{2}{3}$ and $r_2 = \frac{1}{2}$. Then we obtain if the competitive intensity b is sufficiently low, $E\left[\pi_s^C\right] \geq E\left[\pi_s^{FU}\right] > E\left[\pi_s^{FB}\right]$, otherwise $E\left[\pi_s^{FU}\right] > \max\left\{E\left[\pi_s^C\right], E\left[\pi_s^{FB}\right]\right\}$, which can be seen in Figure G1.

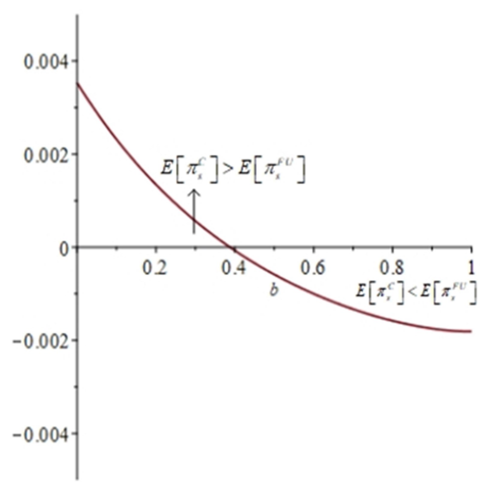

Fig. H1: The impact of b on the suppliers pricing strategy

Let $\sigma^2 = \frac{1}{200}$, $I = 1$, $a = 1$, $c = \frac{1}{4}$, $r_2 = \frac{1}{4}$ and $b = \frac{1}{2}$, we have T is increasing in r_1. Then if buyer 1's capability of process innovation is high enough, i.e., $r_1 \geq \overline{r_1}$, $E\left[\pi_s^C\right] \geq E\left[\pi_s^{FU}\right] > E\left[\pi_s^{FB}\right]$, otherwise $E\left[\pi_s^{FU}\right] > \max\left\{E\left[\pi_s^C\right], E\left[\pi_s^{FB}\right]\right\}$, which can be seen in Figure G2.

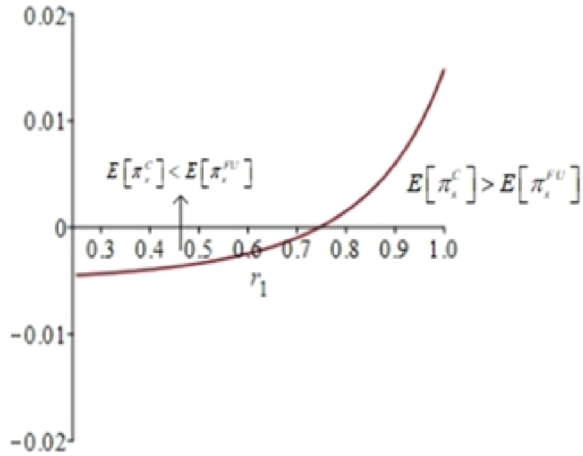

Fig. H2: The impact of r_1 on the suppliers pricing strategy

Let $\sigma^2 = \frac{1}{200}$, $I = 1$, $a = 1$, $c = \frac{1}{4}$, $r_1 = \frac{3}{4}$ and $b = \frac{1}{2}$, we have T is increasing in r_2. Then if buyer 2's capability of process innovation is high enough, i.e., $r_2 \geq \overline{r_2}$, $E\left[\pi_s^C\right] \geq E\left[\pi_s^{FU}\right] > E\left[\pi_s^{FB}\right]$, otherwise $E\left[\pi_s^{FU}\right] > \max\left\{E\left[\pi_s^C\right], E\left[\pi_s^{FB}\right]\right\}$, which can be seen in Figure G3.

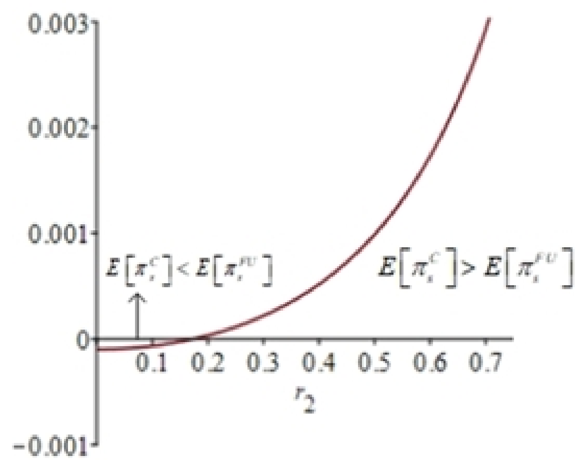

Fig. H3: The impact of r_2 on the suppliers pricing strategy

Table H1: The impacts of model parameters on optimal decisions

$Parameter$	θ_i^{FB*}	θ_i^{C*}	θ_i^{FU*}	$E\left[w_i^{FB*}\right]$	$E\left[w^{C*}\right]$	$E\left[w^{FU*}\right]$
a	$+$	$+$	$+$	$+$	$+$	$+$
b	$\pm$	$\pm$	$\pm$	$\pm$	0	$\pm$
c	$-$	$-$	$-$	$-$	$-$	$-$
r_i	$+$	$+$	$+$	$+$	0	$+$
r_j	$-$	$-$	$-$	$-$	0	$+$
I	$-$	$-$	$-$	$-$	0	$-$