PRICING AND QUALITY DECISIONS IN A SUPPLY CHAIN WITH CONSUMERS’ PRIVACY CONCERN

YOU ZHAO, ZIBIN CUI, JIANXIN CHEN AND RUI HOU*

School of Management, Guangdong University of Technology
Guangzhou, Guangdong 510520, China

(Communicated by Gerhard-Wilhelm Weber)

Abstract. This study considers a supply chain consists of one manufacturer produces a product with a quality level and sells it through one retailer. A stylized model is developed to investigate the impacts of consumers’ privacy concerns on pricing, quality decisions, and profitability through the relationship between product quality and personal information. When consumers’ privacy concern is considered, the product quality level, the wholesale price, the payoffs of the manufacturer and retailer, and consumer surplus decrease with the personal information loss, whereas the selling price increases if this loss is low. Our results also show that the retailer prefers to charge a high selling price if the information benefit and the personal information loss are low, or the information benefit is relatively high. Moreover, a “win-win-win” outcome can be achieved among the manufacturer, retailer, and consumers if the personal information loss is sufficiently low. In the case of quality-differentiated products, however, although the manufacturer improves the product quality level, the wholesale prices are increased if the information benefit and the personal information loss are low, or the information benefit is high.

1. Introduction. This study explores how consumers’ privacy concern affects pricing, quality decisions, profitability, and consumer surplus in a supply chain. We analyze the relationship between product quality and personal data.

With the advent of the big data era, consumer privacy protection is facing growing challenges. The more personal information an organization gathers, the more likely consumers’ privacy will be leaked. Organizations or individuals who acquire consumers’ information from illegal channels may sell them various products, cheat them via SMS or telephone, or steal their financial information directly. Further, such privacy disclosure will result in consumer distress, even exposing them to potential risks. The General Data Protection Regulation (GDPR), established in the European Union (EU)¹, implements regulations for organizations that provide goods and services to the people of the EU, or collect and analyze data related to EU residents, irrespective of the businesses’ locations. Accordingly, [7] study the impact of privacy regulation on product quality and consumer surplus under monopoly and competition scenarios. Practically, however, the impacts of consumers’ privacy concern on pricing, quality decisions, and profitability in a supply chain are

---

*Corresponding author: Rui Hou.

1Source: https://gdpr.eu/what-is-gdpr/ (accessed on Mar. 23, 2021).
also significant and interesting issues. Therefore, this study is the first to investigate the interplay between product quality and personal information in a supply chain.

It is challenging to intuitively imagine the relationship between product quality and personal information from the consumers’ perspective in a supply chain, especially for the customized products [33]. Therefore, we provide several examples to explain this. Currently, Under Armour produces high-tech shoes and sells them on Amazon.com (see Figure 1). The shoes are equipped with a high sensitivity Bluetooth built-in chip, which can be linked with the UA run phone app to accurately record running data. Users, whether running enthusiasts or those seeking to lose weight, can customize their training plan through the app. In other words, high-tech quality shoes are related to a high degree of sophistication or complexity, and if consumers decide to share personal data to avail better add-on services, then they can obtain an information benefit [13, 7]. Similarly, Keep sells the keepkit series of intelligent hardware products, such as treadmills. Through its linkage with the Keep app, Keep can obtain users’ personal information and set different modes and speed limits to achieve the required movement goals, so as to obtain a better usage experience. Particularly, we conjecture that the benefits of sharing data increase with the product quality level.

Figure 1. Under Armour HOVR Phantom

From the aforementioned examples, it is clear that consumers face a trade-off problem regarding whether to share personal data to avail better add-on services derived from the product quality. Consequently, we investigate the following important and practical issues.

---

2HOVR Phantom: The laser perforated microthread body is ventilated and equipped with a fabric collar and heel TPU stabilizer to provide complete stability and a soft and comfortable packaging experience. [https://www.amazon.com/Under-Armour-Mens-Phantom-Running/dp/B074ZPLH95](https://www.amazon.com/Under-Armour-Mens-Phantom-Running/dp/B074ZPLH95) (accessed on Mar. 23, 2021).

3One may concern that what is exactly the meaning of “information benefit”, we explain it here. To some extent, we can regard “information benefit” as “add-on service”. For example, when consumers use UA run app, they face personal information loss, while this app provides better add-on service. Also, such information benefit shared by consumers. Note that there is no sort of discount associated with information benefit.

4Source: [https://www.gotokeep.com/](https://www.gotokeep.com/) (accessed on Mar. 23, 2021).
Should consumers share their personal data to avail better add-on services derived from the product quality?

How does the consumers’ privacy concern affect pricing, quality decisions, and profitability in a supply chain?

To address these issues, we develop a stylized model to investigate the impacts of the consumers’ privacy concern on pricing, quality decisions, and profitability in a supply chain. We consider that in a one-to-one supply chain, a manufacturer produces a product with a certain quality level and sells it to the retailer at a wholesale price and the retailer then sells it to the consumers at a particular selling price. We assume that the manufacturer acts as the Stackelberg leader and the retailer as the Stackelberg follower. Consumers will decide whether to share their personal data based on their utility. Two modes are considered, that is, (i) a benchmark, mode N, in which consumers do not share personal data; and (ii) mode S, where consumers share their personal data.

Our contributions can be summarized as follows.

• When the consumers’ privacy concern is considered, the product quality level, wholesale price, the payoffs of the manufacturer and retailer, and consumer surplus decrease with the personal information loss, whereas the selling price increases if the level of this loss is low.

• Further, when the information benefit increases, the optimal selling price, wholesale price, product quality, consumer surplus, and the payoffs of the manufacturer and retailer increase. Our results also show that the manufacturer should increase the product quality level, thereby increasing the wholesale price.

• However, the retailer prefers to charge a high selling price if the information benefit and the personal information loss are low, or the information benefit is relatively high. Moreover, we find that a “win-win-win” outcome can be achieved among the manufacturer, retailer, and consumers if the personal information loss is sufficiently low.

• In the case of quality-differentiated products, however, although the manufacturer improves the product quality level, the wholesale prices are increased if the information benefit and the personal information loss is low, or the information benefit is high. Additionally, we show that the gap among quality level, wholesale price, and selling price for two products increased with the information benefit and decreased with the personal information loss.

The remainder of this study is constructed as follows. Section 2 reviews the previous literatures. We develop a stylized model in Section 3. Section 4 presents the analysis under different modes and our analytical results. Next, we extend our basic model in Section 5. Finally, we conclude the paper and propose future research paths in Section 6. All proofs are shown in the Appendix.

2. Literature review. Our paper relates to the literature on consumers’ privacy concern in operations management [32, 11]. [38] investigate the effect of consumers’ privacy on economic efficiency. [1] conduct a review summarizing the linkages among different streams of theoretical and empirical research on the economics of privacy. [20] investigate how should a firm (who can collect personal information about consumers) price its service while considering consumers’ privacy concern. Another related literature stream explores the linkage between consumers’ privacy and price discrimination. [22] study the impact of consumers’ information privacy concern on
personalized pricing, in which firms compete at different levels for personalization. They show that a firm with inferior utilization ability is more affected by consumer privacy concerns. [6] develop a model that allows a company and a heterogeneous person to choose to keep their anonymity in order to avoid being identified as past consumers. The results show that it is easy for consumers to keep their anonymity, which can bring high profits for enterprises, and increasing the cost of anonymity can benefit consumers. [3] study two competing firms with privacy and find that a high level of privacy leads to a better service derived by competition, however, higher competition intensity does not necessarily improve privacy when consumers’ willingness to pay is low. [23] study voluntary profiling, where refusals to participate lead the monopolist to charge high prices, which decreases the consumers’ search costs of finding the ideal product while yields unsolicited advertisements. [35] investigate the impacts of price discrimination on prices, profits, and consumer surplus when firms can purchase the consumers’ information from a third-party firm and show that decision makers should pay more attention to deter exclusivity deals rather than enabling consumers to protect their privacy easily. Moreover, [9] analyze the role of application license requests in privacy for mobile service. Meanwhile, [4] employ Psychological Reactance Theory to study the effect of privacy concern in an omnichannel environment. [7] study the optional joining mechanism of privacy regulation, which will affect product quality and consumer surplus, and consumers have the ability to decide whether to share personal data. The results show that the trade-off between information and quality is sufficient, and the product quality under the selective joining system is higher than that without the selective joining system. In contrast to the above-mentioned studies, we focus on the impacts of consumers’ privacy concern on product quality in a supply chain that consists of one manufacturer and one retailer.

Our study is also related to the product quality in operations management [21, 19, 41, 37]. [21] study a supply chain in which the manufacturer produces a product and sells it to the retailer, and shows that the manufacturer is more willing to sell higher quality products through his own channel than through the retailer’s channel. [40] and [36] investigate the pricing and quality decision in a supply chain where the manufacturer sells a product through a direct channel or the retailer’s channel. [5] study a supply chain in which manufacturers can sell their products through retail channels, direct channels or dual channels of retail and direct channels. The results show that the performance of the supply chain can be improved by adding new channels considering the pricing and quality decisions. [39] investigate quality competition between two manufacturers when price, quality decision, and customer loyalty are considered. They show that manufacturers can benefit from higher quality ratings from consumers, strong loyalty and channel concentration. [25] study the product quality in centralized and decentralized supply chains, and find that the uncertainty of market size reduces the quality difference, which depends on the degree of consumer heterogeneity. [42] the information sharing problem in a dual channel supply chain in which the manufacturer invests in product quality but the retailer cannot observe it. They show that the manufacturer prefers to give up their pricing power if the exogenous wholesale price is moderate. Another stream focuses on product line design for quality-differentiated products. [31] focus on a monopolist that chooses a high-quality location to serve a heterogeneous consumer market. [10] study the problem of congruence in product line design, because the products in the product line are partial substitutes, and
consumers can choose the products they want to buy for multi product companies. [43] study probabilistic selling for quality-differentiated products, and find that even if the endogenous quality is selected, probability sales as a way of profit disposal of excess capacity appears in the quality differentiation market. [18] investigate the manufacturer encroachment problem in which consumers have a heterogeneous preference for product quality in a supply chain. They show that in the case of endogenous quality, the manufacturer encroaches upon the retailer’s market share in most cases; however, only when the manufacturer’s quality cost is relatively high will the retailer’s profit remain unaffected. Further, [8] indicate the encroachment behavior can make the manufacturer improve the product quality in a supply chain. Unlike the above research, this paper restricts our attention to how the consumers’ privacy concerns affect the supply chain members’ decision when consumers’ personal information disclosure due to the use of high-quality service products. Table 1 compares this paper and representative literatures.

3. Notation, assumption, and problem formulation. We consider a supply chain where a manufacturer (referred to as subscript “M”) produces a product with a quality level \( q > 0 \) and sells it at a wholesale price \( w > 0 \) to a retailer (referred to as subscript “R”). Following the work of [30, 40, 24], the unit product cost is assumed as a quadratic function form, that is, \( C(q) = \eta q^2 \), and we assume that \( \eta = 1 \) in our study. It is worth noting that this assumption will not affect our main findings. According to [12, 24], the retailer can sell this product to consumers at a retail price \( p \). As explained in Section 1, consumers may face a trade-off problem, that is, if personal data is shared, consumers will suffer personal information loss, however, they also simultaneously avail better add-on services from the product quality. We use \( c > 0 \) to denote the consumers’ personal information loss; This assumption is widely adopted in the privacy concern literatures [22, 6, 3, 35]. Consequently, consumers should determine whether to share personal data when they face a purchasing decision. Let \( X \) denote consumers’ personal data sharing decision for a product, where \( X = 1 \) if consumers share personal data, and \( X = 0 \) otherwise. Figure 2 depicts the supply chain structure.

Based on the above description, the net utility of a consumer purchased product is given by

\[
U = \theta q - p + (bq^k - c)X, \tag{1}
\]

where \( \theta \) denotes the consumers’ willingness to pay for the quality of the product, and \( bq^k \) represents the benefits from personal information provision for the product. A higher \( b \in (0, 1) \) and \( k > 0 \) lead to a higher information benefit. For analytical
convenience, in our study, we assume that $k = 1$. This information benefits form and assumption are in line with [7]. Moreover, consumers are heterogeneous concerning their willingness to pay for product quality $\theta$, which is uniformly distributed over support $[0, 1]$. Notably, we normalize the mass of customers in the considered market to one. This setting is in line with [24]. Table 2 presents the notations appeared in our study.

### Table 2. Notations

| Super(sub)scripts | Explanation |
|-------------------|-------------|
| S                 | consumers share personal information |
| N                 | consumers not share personal information |
| H                 | high-quality product |
| L                 | low-quality product |

| Parameters        | Explanation                                         |
|-------------------|-----------------------------------------------------|
| $\theta$          | willingness to pay for product quality, $\theta \sim U[0, 1]$ |
| $b$               | information benefit coefficient from product quality, $b \in (0, 1)$ |
| $c$               | consumers’ personal information loss, $c > 0$ |
| $X$               | binary decision parameter for consumers’ data sharing, $X = 0, 1$ |

| Decision Variables | Explanation |
|--------------------|-------------|
| $p$                | product’s selling price |
| $q$                | product’s quality level |
| $w$                | product’s wholesale price |
| $\pi_M$            | payoff of the manufacturer |
| $\pi_R$            | payoff of the retailer |
| $CS$               | consumer surplus |

The timeline of the game is as follows. First, the manufacturer determines the product quality, and then the wholesale price is decided. Next, the retailer announces the selling price of the product. We assume that the manufacturer acts as the Stackelberg leader, and the retailer acts as the Stackelberg follower. As generally, the utility is assumed as strictly concave ($k < 1$) or in a liner form ($k = 1$) in quality to ensure analytical convenience. However, in Section 5, we discuss a case where $k > 1$ is also suitable [2, 7].
indicated in Section 1, our main goal is to study the impacts of the consumers’ privacy concern on pricing, quality decisions, and profitability in a supply chain. Let “S” (“N”) denote the case where consumers share (do not share) personal data. Therefore, we investigate the following two modes:

- **A benchmark: Mode “N”**. We begin with a benchmark case to better depict the impacts of the consumers’ privacy concern on the behaviors of firms, in which the consumers don’t share personal data for the product, i.e., $X = 0$.

- **Mode “S”**. Under this mode, consumers are willing to disclose personal data for the product, that is, $X = 1$.

We present the analysis for the two modes in the next section and assume that $c \leq \frac{1 + 2b + b^2}{4}$ in our study, to avoid trivial cases.

4. **Equilibrium analysis.** We derive the equilibrium outcomes under Modes “S” and “N,” respectively. We begin with a benchmark case where consumers prefer to not share personal data and then consider the case where consumers share personal data. Next, we study the impacts of consumers’ privacy on pricing, quality decisions, profitability by comparing Modes “S” and “N.”

4.1. **Analysis of mode “N”**. Under this mode, consumers withhold personal data for the product. Since $X$ equals to zero, the net utility of a consumer purchasing product can be rewritten as follows: $U = \theta q - p$. Consumers decide to purchase a product if and only if the net utility is greater than or equal to zero. That is, they purchase the product if and only if $\theta q - p \geq 0$. Let $D^N$ denote the demand for the product. We can easily obtain the demand for the product as follows: $D^N = 1 - \frac{p}{q}$. Therefore, the payoff function of the manufacturer and retailer and consumer surplus are respectively given by

$$\pi_M^N = (w - q^2)D^N, \pi_R^N = (p - w)D^N,$$

$$CS^N = \int_{\frac{1}{2}}^{1} (\theta q - p) d\theta.$$  \hspace{1cm} (3)

Accordingly, the following lemma states the equilibrium outcomes under this mode.

**Lemma 4.1.** Under Mode “N,”

(a) the optimal selling price, wholesale price and quality for product are respectively given by $p^N = \frac{5}{18}, w^N = \frac{2}{9},$ and $q^N = \frac{1}{3};$

(b) the manufacturer’s payoff and the retailer’s payoff are respectively given by $\pi_M^{N*} = \frac{1}{18}$ and $\pi_R^{N*} = \frac{1}{108};$

(c) consumer surplus is given by $CS^{N*} = \frac{1}{216}$.

Lemma 4.1 clearly indicates that the following relationship holds: $\pi_M^{N*} = 2\pi_R^{N*} = 4CS^{N*}$. Next, we present the analysis of Mode “S.”

4.2. **Analysis of mode “S”**. Under this mode, consumers share personal data for the product. Since $X$ equals to one, we rewrite the net utility of a consumer purchasing product as follows: $U = \theta q - p + bq - c$. Consumers decide to purchase a product if and only if the net utility is greater than or equal to zero. That is, they purchase the product if and only if $\theta q - p + bq - c \geq 0$. Let $D^S$ denote the demand for the product under this mode. The demand for the product can be derived as follows: $D^S = 1 - \frac{p - bq + c}{q}$.
Based on this, the payoff function of the manufacturer and retailer and consumer surplus under Mode “S” are given by
\[ \pi_M^S = (w - q^2)D^S, \]
\[ \pi_R^S = (p - w)D^S, \]
and
\[ CS^S = \int_{bq}^{1+bq+c}(\theta q - p + bq - c)\,d\theta, \]
respectively. Therefore, the following lemma can be obtained.

**Lemma 4.2.** Under Mode “S,”
(a) the optimal selling price, wholesale price and quality for the product are respectively given by
\[ p^*_S = \frac{5}{36} (1 + b) - \frac{2}{3} c, \]
\[ w^*_S = \frac{1}{9} [(1 + b)A - 3c], \]
and
\[ q^*_S = \frac{1}{6} A; \]
(b) the manufacturer’s payoff and the retailer’s payoff are respectively given by
\[ \pi_M^S = \frac{A}{108A} \text{ and } \pi_R^S = \frac{2B}{216A}; \]
(c) consumer surplus is given by
\[ CS^S = F_1(b, c); \]
where
\[ A = (1 + b) + \sqrt{12c + (1 + b)^2}, \]
and the value of \( F_1(b, c) \) can be found in Appendix.

By Lemma 4.2, we also find that the following relationship holds:
\[ \pi_R^S = \pi_M^S \frac{5}{36}, \]
which is similar to Lemma 4.1. Next, we investigate the impacts of the information benefit and personal information loss on equilibrium solutions, as stated in the following proposition.

**Proposition 1.** In equilibrium, the following relationships hold:

(i) \( \frac{\partial p^*_S}{\partial c} > 0 \) if \( c < \frac{5+10b+5b^2}{484} \), \( \frac{\partial w^*_S}{\partial c} > 0 \), \( \frac{\partial q^*_S}{\partial c} > 0 \), \( \frac{\partial D^*_S}{\partial c} < 0 \),
\( \frac{\partial CS^*_S}{\partial c} < 0 \).

(ii) when \( b \) increases, the optimal selling price, wholesale price, product quality, the payoffs of the manufacturer and retailer, and consumer surplus increase.

One may assume that the optimal selling price always increases with the personal information loss as we often see real life examples of price discrimination. However, based on Proposition 1(i), the optimal selling price of the product is not monotone in \( c \), that is, the optimal selling price decreases with \( c \) if \( c < \frac{5+10b+5b^2}{484} \) and increases with \( c \) if \( c \geq \frac{5+10b+5b^2}{484} \). In other words, the retailer should decrease the selling price to attract consumers even if the product quality level is improved. This result sheds light on the relationship between the information benefit and personal information loss. Moreover, we find that the optimal wholesale price and quality level increase with the personal information loss. This result is reasonable. As explained in Section 1, consumers face a trade-off problem regarding whether to share personal data to avail a better add-on service (information benefit). Therefore, when consumers share personal data, they also pay a higher weight on the information benefit, and the manufacturer then prefers to improve the product quality level to attract consumers and increase the wholesale price to ensure revenues if consumers incur a higher personal information loss. Additionally, we show that the optimal payoffs of the manufacturer and retailer and consumer surplus always decrease with the personal information loss because the demand decreases with the personal information loss.

Reasonably, Proposition 1(ii) demonstrates that the retailer pursues to increase the optimal selling price when consumers obtain a high information benefit. Conversely, the manufacturer prefers to enhance the product quality to appeal to consumers, and the wholesale price is reduced. Moreover, the demand increases in \( b \) will result in higher payoffs for the manufacturer and retailer and consumer surplus.
4.3. Impacts of consumers’ privacy concern. Combining Lemma 4.1 with Lemma 4.2, we study the impacts of consumers’ privacy concern on pricing, quality decisions, and firm’s profitability in a supply chain. The results are characterized in the following theorem.

**Theorem 4.3.** In equilibrium,

(a) \( p^S_\ast > p^N_\ast \) if \( b \leq \sqrt{\frac{3}{10}} \) and \( c < \frac{5(A + B)}{96} \) or \( b > \sqrt{\frac{3}{10}} \);

(b) \( w^S_\ast > w^N_\ast \);

(c) \( q^S_\ast > q^N_\ast \);

(d) \( D^S_\ast > D^N_\ast \) if \( c < \frac{2b + 3b^2}{12} \);

(e) \( \pi^S_M_\ast > \pi^N_M_\ast \) if \( c < A_1(b) \), \( \pi^S_R_\ast > \pi^N_R_\ast \) if \( c < A_2(b) \);

(f) \( CS^S_\ast > CS^N_\ast \) if \( c < A_3(b) \);

where \( A = 1 + 18b + 8b^2 \) and \( B = \sqrt{1 + 164b + 406b^2 + 324b^3 + 81b^4} \).

Theorem 4.3(a) indicates that when the consumers’ privacy concern is considered, there exist two thresholds \( \sqrt{\frac{3}{10}} \) and \( \frac{5(A + B)}{96} \), such that the optimal selling price should be increased by the retailer if \( b \leq \sqrt{\frac{3}{10}} \) and \( c < \frac{5(A + B)}{96} \) or \( b > \sqrt{\frac{3}{10}} \).

In other words, compared with Mode “N,” when the information benefit and personal information loss are low, or the information benefit is high, the retailer should charge a higher selling price to consumers. Parts(b) and (c) state that the manufacturer will improve the product quality to attract consumers and will increase the wholesale price. Part(d) shows that the demand under Mode “S” is not always higher than that under Mode “S.” Concretely, when the consumers’ privacy concern is considered, the demand is increased if the personal information loss is low.

We next analyze parts(e) and (f). It is clear that the payoffs of the manufacturer and retailer and consumer surplus under Mode “S” are not always higher than that under Mode “N.” In other words, the manufacturer, retailer, and consumers do not always benefit from the personal information loss. That is, there exist three thresholds \( A_1(b) \), \( A_3(b) \), and \( A_3(b) \), such that the payoff the manufacturer under Mode “S” is higher than that under Mode “N” if the personal information loss is moderate, the payoff of the retailer under Mode “S” is higher than that under Mode “N” if the personal information loss is low, consumer surplus under Mode “S” is higher than that under Mode “N” if the personal information loss is relatively low. Unfortunately, thresholds \( A_1(b) \), \( A_3(b) \), and \( A_3(b) \) cannot be derived analytically. We present a numerical example and set \( b = 0.6 \) and modify \( c \) from 0 to 0.5, as shown in Figure 3. We find that the payoffs of the manufacturer and retailer and consumer surplus decrease with the personal information loss, which is in line with Proposition 1(i). Interestingly, we show that a “win-win-win” outcome can be achieved, that is, the manufacturer, retailer, and consumers benefit from the consumers’ privacy concern, if the personal information loss is low. This result is reasonable because parts(a) and (d) show that a higher personal information loss leads to a higher selling price and market demand, which enables the firms to gain more profits and increase consumer surplus.

5. Discussion. Our basic model assumes that one manufacturer produces a product with a certain quality level and sells it to one retailer. In order to simplify the analysis, we ignore the general form of information revenue and the situation that manufacturers design product lines in vertical differentiated supply chain. We extend our basic model to examine the robustness in this section.
5.1. General information benefit form. In our basic model, we assume the information benefit form as $bq$ if consumers share personal data. We then consider a general information benefit form, that is, $bq^k$ and $k = 2$. The convexity of utility function is applicable to some cases, such as ERP system. In this case, the benefits of additional services may increase with the complexity of core products.

We summarize the equilibrium solutions in the following lemma.

**Lemma 5.1.** Under Mode “S,”
(a) the optimal selling price, wholesale price and quality for product are respectively given by $p_S^* = \frac{-A(-5+3b)+12c(b-1)(3b-2)}{36(1-b)^2}$, $w_S^* = \frac{-A(b-2)+6c(b-1)(2b-1)}{18(1-b)^2}$, and $q_S^* = \frac{1}{6(1-b)}A$;
(b) the manufacturer’s payoff and the retailer’s payoff are respectively given by $\pi_M^S = \frac{-(A+12c(b-1))^2}{108(1-b)^2}$ and $\pi_R^S = \frac{\pi_M^S}{2}$;
(c) consumer surplus is given by $CS^S$ as shown in Appendix;
where $A = 1 + \sqrt{1 - 12c(-1 + b)}$.

Lemma 5.1 is similar to Lemma 4.2, while we focus on investigating the impacts of $k$ on the firm’s profitability and consumer surplus. Given the complexity of the analysis, we adopt numerical simulations, and the results are shown in Figure 4.

From Figure 4, we find that when $k$ is large, the payoffs of the manufacturer and retailer and consumer surplus always decrease with the personal information loss. Moreover, a “win-win-win” outcome still holds between the manufacturer, retailer, and consumers. Meanwhile, we also find that consumers prefer to share personal data when $b$ is small. We summarize the results in the following proposition.

**Proposition 2.** When $k$ is large, a “win-win-win” outcome also can be achieved among the manufacturer, retailer and consumers.
5.2. Quality-differentiated products. In practice, retailers may sell a variety of products that are vertically differentiated from manufacturers. For example, Under Armour not only sells HOVR Phantom on Amazon.com, but also sells HAVR Sonic, a low quality product, as shown in Figure 5. Therefore, we consider a supply chain where a manufacturer (referred to as subscript “M”) produces two quality-differentiated products, a high-quality product (referred to as subscript “H”) with a quality level $q_H > 0$, a low-quality product (referred to as subscript “L”) with a quality level $q_L > 0$, and sells them at wholesale prices $w_H > 0$ and $w_L > 0$.

---

6HOVR Sonic: Positioning in the transparent and agile HOVR Sonic, it is perceived as a cushioning running shoe that enables faster running due to its composite fabric body filled with super large air holes. [https://www.amazon.com/Under-Armour-Mens-Sonic-Running/dp/B07PWNL8NP?th=1&psc=1](https://www.amazon.com/Under-Armour-Mens-Sonic-Running/dp/B07PWNL8NP?th=1&psc=1) (accessed by Mar. 23, 2021).
respectively. The net utility of a consumer purchasing product $j$ ($j = H, L$), is given by

$$U_H = \theta q_H - p_H + (bq_H^k - c)X, \quad U_L = \theta q_L - p_L + (bq_L^k - c)X.$$ (4)

This subsection presents the equilibrium outcomes and investigates the impacts of the consumers’ privacy concern on them under two modes for the two quality-differentiated products. The timeline of the game is as follows. The manufacturer first determines product $j$’s quality $q_j$ and sets product $j$’s wholesale price $w_j$ to the retailer. Finally, the retailer announces the selling price $p_j$ to the end market for product $j$ ($j = H, L$) by maximizing the profit. We solve the game backwardly. First, the retailer should announce the product’s selling price. After that, according to the retailer’s action, the manufacturer decides the product quality level, and then announces the wholesale price for the product. Figure 6 depicts the supply chain structure. Note that other settings are in line with our basic model as shown in Section 3.
5.2.1. Analysis of mode “N”. Under this mode, consumers withhold personal data for both products. Since $X$ equals to zero, the net utility of a consumer purchasing product $j$ ($j = H, L$) can be rewritten as follows: $U_H = \theta q_H - p_H$ and $U_L = \theta q_L - p_L$. Consumers decide to purchase a product if and only if the net utility is greater than or equal to zero. That is, they purchase a high (low)-quality product if and only if $\theta q_H - p_H \geq \theta q_L - p_L$ and $\theta q_L - p_L \geq 0$. Therefore, we ignore these scenarios.

From Lemma 4.1(a), we find that the gap among the optimal selling price, wholesale price and product quality for both products, respectively. We can easily obtain the demands for product $j$ as follows: $D^N_H = 1 - \frac{p_H - q_H}{q_H - q_L}$ and $D^N_L = \frac{p_L - q_L}{q_L - q_H} - \frac{p_L}{q_L}$. Therefore, the payoff function of the manufacturer and retailer and consumer surplus are respectively given by

$$\pi^N_M = (w_H - q^2_H)D^N_H + (w_L - q^2_L)D^N_L,$$
$$\pi^N_R = (p_H - w_H)D^N_H + (p_L - w_L)D^N_L,$$
$$CS^N = \int_{q^L_N}^{q^L_N} (\theta q_H - p_H) d\theta + \int_{q^L_N}^{q^L_N} (\theta q_L - p_L) d\theta.$$ (7)

Accordingly, the following lemma states the equilibrium outcomes under this mode.

**Lemma 5.2.** Under Mode “N,”
(a) the optimal selling price, wholesale price and product quality $j$ ($j = H, L$) are respectively given by $p^*_H = \frac{17}{50}$, $p^*_L = \frac{4}{25}$, $w^*_H = \frac{7}{25}$, $w^*_L = \frac{3}{25}$, $q^*_H = \frac{2}{5}$, and $q^*_L = \frac{1}{5}$;
(b) the manufacturer’s and retailer’s payoffs are given by $\pi^*_M = \frac{1}{50}$ and $\pi^*_R = \frac{1}{100}$, respectively;
(c) consumer surplus is given by $CS^*_N = \frac{1}{250}$.

From Lemma 4.1(a), we find that the gap among the optimal selling price, wholesale price, and product quality equal to $\frac{9}{50}$, $\frac{4}{25}$, and $\frac{1}{5}$, respectively. Moreover, it is clear from part(b) that the following relationship holds: $\pi^*_M = 2\pi^*_R = 4CS^*_N$.

5.2.2. Analysis of mode “S”. Under this mode, consumers share personal data for both products. Since $X$ equals to one, we rewrite the net utility of a consumer purchasing product $j$ ($j = H, L$) as follows: $U_H = \theta q_H - p_H + bq_H - c$ and $U_L = \theta q_L - p_L + bq_L - c$. Consumers decide to purchase a product if and only if the net utility is greater than or equal to zero. That is, they purchase a high (low)-quality product if and only if $\theta q_H - p_H + bq_H - c \geq \theta q_L - p_L + bq_L - c$ and $\theta q_L - p_L + bq_L - c \geq 0$. Therefore, the payoff function of the manufacturer and retailer and consumer surplus under Mode “S” are respectively given by

$$\pi^S_M = (w_H - q^2_H)D^S_H + (w_L - q^2_L)D^S_L,$$
$$\pi^S_R = (p_H - w_H)D^S_H + (p_L - w_L)D^S_L,$$
$$CS^S = \int_{q^L_S}^{q^L_S} (\theta q_H - p_H + bq_H - c) d\theta + \int_{q^L_S}^{q^L_S} (\theta q_L - p_L + bq_L - c) d\theta.$$
and $q$ we assume that the consumers’ information benefit is related to the quality level benefit coefficient if and only if the personal information loss is low. In our model, ever, the payoffs of the manufacturer and retailer increase with the information loss to appeal to consumers, whereas the wholesale price of the high-quality product increases if and only if the information loss is sufficiently low, and the optimal wholesale price of the low-quality product always increases with it. This is the reason the optimal selling price of the high-quality product does not always increase with the personal information loss. Interestingly, we find that the optimal quality of the two products is increased with increasing $b$, and the value of $F_2(b,c)$ is presented in the Appendix.

Based on Lemma 5.3, we next investigate the impacts of the personal information loss $c$ and the information benefit coefficient $b$ on the equilibrium outcomes, respectively, as stated in the following proposition.

**Proposition 3.** In equilibrium, the following relationships hold:

(i)  \[
\begin{align*}
\frac{\partial p_H^*}{\partial b} &> 0 \text{ if } c < \frac{5+10b+5b^2}{484}, \quad \frac{\partial p_H^*}{\partial c} > 0; \\
\frac{\partial w_H^*}{\partial b} &> 0 \text{ if } c < \frac{2+4b+2b^2}{49}, \quad \frac{\partial w_H^*}{\partial c} > 0; \\
\frac{\partial p_L^*}{\partial b} &> 0, \quad \frac{\partial p_L^*}{\partial c} > 0; \\
\frac{\partial \pi_M^*}{\partial c} &< 0, \quad \frac{\partial \pi_R^*}{\partial c} < 0; \\
\frac{\partial \text{CS}^*}{\partial c} &< 0.
\end{align*}
\]

(ii) when $b$ increases, the optimal selling price, wholesale price, product quality $j$ ($j = H, L$), the payoffs of the manufacturer and retailer, and consumer surplus increase.

(iii) \[
\begin{align*}
\frac{\partial (p_H^* - q_H^*)}{\partial b} &< 0, \quad \frac{\partial (w_H^* - q_H^*)}{\partial b} < 0, \quad \frac{\partial (q_H^* - q_L^*)}{\partial b} < 0; \\
\frac{\partial (p_L^* - q_L^*)}{\partial b} &> 0, \quad \frac{\partial (w_L^* - q_L^*)}{\partial b} > 0, \quad \frac{\partial (q_L^* - q_H^*)}{\partial b} > 0.
\end{align*}
\]

Proposition 3(i) states that the selling price of a high-quality product increases with the personal information loss if and only if the loss is sufficiently low, while the selling price of the low-quality product always increases with it. This result is reasonable. The intuition is that if the manufacturer decides to improve the product quality level, then the wholesale prices should be increased simultaneously. Interestingly, we find that the optimal quality of the two products is increased with the personal information loss to appeal to consumers, whereas the wholesale price of the high-quality product increases if and only if the information loss is sufficiently low, and the optimal wholesale price of the low-quality product always increases with it. This is the reason the optimal selling price of the high-quality product does not always increase with the personal information loss. Similar to Proposition 1(i), the payoffs of the manufacturer and retailer and consumer surplus increase with the personal information loss.

In part(iii), the optimal selling prices, wholesale prices, and product qualities of the two products benefit from the increased information benefit coefficient. However, the payoffs of the manufacturer and retailer increase with the information benefit coefficient if and only if the personal information loss is low. In our model, we assume that the consumers’ information benefit is related to the quality level
of the two products, which results in a positive impact on the net utility of a consumer. Therefore, such setting makes the consumers’ information benefits sensitive. If the consumers pay a higher weight on information benefits, then the manufacturer should improve the quality level of the two products and increase the wholesale prices. According to this, since the improvement costs of the two products increase, the selling prices also increase by maximizing the payoff.

Proposition 2(iii) indicates that when the personal information loss increases, the gaps among the optimal selling prices, wholesale prices and the qualities of the two products decrease. Moreover, we find that the gap between the optimal selling prices (wholesale prices) of the two products increases with the information benefit coefficient if and only if the personal information loss is sufficiently low (low), and the gap between the optimal quality of the two products always increases with the information benefit coefficient. It is worth noting the personal information loss and information benefit is limited; therefore, the gaps are also limited.

5.2.3. Impacts of consumers’ privacy concern. According to Lemma 5.2 and Lemma 5.3, we compare Modes “N” and “S” to investigate the impacts of consumers’ privacy concern on pricing, quality decisions, demands, firms’ profitability, and consumer surplus in a vertically differentiated supply chain, which are characterized in the following theorem.

Theorem 5.4. In equilibrium,

\( a \cdot p_H^{S*} > p_H^{N*} \) if \( b \leq \frac{\sqrt{34} - 5}{5} \) and \( c < \frac{A+14B}{1210} \), or \( b > \frac{\sqrt{34} - 5}{5} \), \( p_H^{S*} > p_H^{N*} \);

\( b \cdot w_H^{S*} > w_H^{N*} \) if \( b \leq \frac{2 \sqrt{7} - 5}{3} \) and \( c < \frac{C+13D^2}{245} \), or \( b > \frac{2 \sqrt{7} - 5}{3} \), \( w_L^{S*} > w_L^{N*} \);

\( c \cdot q_H^* > q_H^{N*} \), \( q_L^* > q_L^{N*} \);

\( d \cdot D_H^* = D_L^* > D_H^* = D_L^* \) if \( c < \frac{2b+5b^2}{20} \);

\( e \cdot \pi_M^* > \pi_M^{N*} \) if \( c < B_1(b) \), \( \pi_S^* > \pi_S^{N*} \), if \( c < B_2(b) \);

\( f \cdot C_S^* > C_M^* \) if \( c < B_3(b) \);

where \( A = 14 + 1150b + 575b^2 \), \( B = \sqrt{1 + 752b + 1876b^2 + 1500b^3 + 375b^4} \), \( C = 13 + 320b + 160b^2 \), and \( D = \sqrt{1 + 102b + 251b^2 + 200b^3 + 50b^4} \).

Theorem 5.4(a) indicates that the optimal selling price of the high-quality product under Mode “S” is greater than that under Mode “N” if the information benefit is low and the personal information loss is sufficiently relatively low, while the retailer prefers to increase the optimal selling price of the low-quality product when the consumers’ privacy concern is considered. From parts(b) and (c), we show that the manufacturer should improve the product qualities of the two products to attract consumers. However, the manufacturer does not always charge a higher wholesale price for the high-quality product. Concretely, the optimal wholesale price of the high-quality product under Mode “S” is greater than that under Mode “N” if the information benefit and the personal information loss are sufficiently low, while the manufacturer prefers to increase the optimal selling price of the low-quality product when the consumers’ privacy concern is considered. This is a valid explanation for the result obtained from part(a). Moreover, we find that there exist a region where the manufacturer may quote a higher wholesale price for the high-quality product, while the retailer prefers to announce a lower wholesale price when the consumers’ privacy concern is considered by parts(a) and (b).

From Theorem 5.4(c), we first find that the optimal demands for the high-quality and low-quality products are the same both under Modes “S” and “N.” Moreover, the optimal demands for the two products under Mode “S” are greater than those.
under Mode “N” if the personal information loss is low. The reason is that the retailer prefers to strike a balance between the two quality-differentiated products by adjusting the selling prices, that is, the quality gap between the two products will be large. From parts (e) and (f), we show that the payoffs of the manufacturer and retailer and consumer surplus under Mode “S” are not always higher than those under Mode “N.” Unfortunately, the thresholds $B_1(b)$, $B_2(b)$, and $B_3(b)$ cannot be derived analytically. To better understand the impacts of consumers’ privacy concern on the payoffs of the manufacturer and retailer, we illustrate a numerical example, and modify $c$ from 0 to 0.5 as shown in Figure 7. We observe that a “win-win-win” outcome can be achieved among the manufacturer, retailer, and consumers if the personal information loss is low, that is, $c < B_3(b)$. Note that when we attempt to apply different values of $b$, the result still holds. This result is in line with Theorem 4.3. We thus confirm the robustness of our basic model.

6. Conclusion and managerial insights. In this section, we conclude our paper and provide managerial insights according to our obtained findings.

6.1. Conclusion. With the development of information technology, the problem of monitoring the collection and use of personal data has evoked a heated debate in academic and policy circles and drawn people’s attention to the right of privacy. We build a Stackelberg game-theoretic model to investigate the impacts of consumers’ privacy concerns on pricing, quality decisions, and profitability through the interplay between product quality and personal information (Table 3 suggests

![Figure 7. Impacts of consumers privacy concern on firms’ payoff and consumer surplus in a vertically-differentiated supply chain](image-url)
the improvement of our work compared with the related work.\footnote{Recall that \cite{7} study two competing retailers with consumers' privacy concern, while we consider a supply chain with it. Also, in our model, we incorporate the loss of information $c$ for consumers. Our improvement is that the impact of consumer privacy concerns on supply chain members. For the model detail, please see \cite{7}.}). Further, we consider two modes, one where consumers do not share personal data and one where consumers share their personal data. Our basic model can be extended on several aspects including the general information benefit form and product line design.

Table 3. The improvement of our work

| Our work | \cite{7} |
|----------|----------|
| Utility function | $U_i = \theta q_i - p_i + (b q_i^k - c) X$, $i = H, L$ | $U = \theta q - p + b q X$ |
| Retailer's objective function | $\pi_{R,i}^N = (p_i - w_i) D_i^N$, $i = H, L$ | $\pi_R = \int_{\theta_0}^{\theta} P(\theta) d\theta + \int_{\theta}^{1} Pd\theta + \int_{1}^{\theta} Pd\theta - C(q)$ |
| Manufacturer's objective function | $\pi_{M,i}^N = (w_i - q_i^2) D_i^N$, $i = H, L$ | None |

We summarize our major findings below.

- First, \textit{when the manufacturer sells a single product}, the product quality level, wholesale price, payoffs of the manufacturer and retailer, and consumer surplus decrease with the personal information loss, whereas the selling price increases if the personal information loss is low. Moreover, we find that a “win-win-win” outcome can be achieved among the manufacturer, retailer, and consumers if the personal information loss is sufficiently low. Recall that the shoe manufacturer Under Armour sells HOVR Phantom, it should emphasize the benefits of using the product to attract consumers to purchase when the consumers’ privacy concern is low.

- Second, \textit{when the manufacturer sells quality-differentiated products}, the manufacturer prefers to increase the product quality level and the wholesale prices if the information benefit and personal information loss are low, or the information benefit is high. Also, we show that the gap among the quality levels, wholesale prices, and selling prices for the two products increases with the information benefit and decreases with the personal information loss. Recall that Under Armour decides to sell HOVR Sonic, it should improve the product quality when the consumers’ privacy concern is low.

Our model is developed on some assumptions, which suggests several directions can be explored. First, we consider that a supply chain consists of one manufacturer and one retailer. It is worth exploring a supply chain in which horizontal competition exists, that is, multiple manufacturers or multiple retailers. Second, if the direction of the sustainable supply chain can be considered, which may be an interesting problem \cite{29, 28, 27, 26}. Third, we develop a single period to investigate the impacts of the consumers’ privacy concerns on pricing, quality decisions, and profitability. An interesting extension would be to develop a multi-period model while considering price discrimination. Fourth, it is worth considering the uncertainty of market demand, outliers in the supply chain, which may lead to different equilibrium \cite{14, 34, 15, 16, 17}. Fifth, while we consider that the retailer sells the product through one channel, it would be beneficial to study a scenario where the retailer distributes the quality-differentiated product through different channels. Last but not least, due to the increased number of online purchase consumers and recently
boosted by COVID pandemics, the impact of privacy concerns should be considered in online intermediary platforms.

6.2. Managerial insights. Our analysis is conducted by exploring the relationship between product quality and personal information.

- For the single product, our findings show that the manufacturer, the retailer, and consumers may benefit from consumers’ data sharing. In other words, if the loss of personal information is high, then the “win-win-win” outcome among the manufacturer, the retailer, and consumers cannot be achieved. Therefore, the retailer should increase the selling price for the product when both the information benefit coefficient is low and the loss of personal information is low, or the information benefit coefficient is high. However, the manufacturer always increases the product quality, and thereby the wholesale price is increased to induce consumers to share their data.

- For the quality-differentiated products, the retailer should increase the selling price for the high-quality product when both the information benefit coefficient is low and the loss of personal information is low, or the information benefit coefficient is high, whereas always increase the selling prices of the low-quality product. On the other hand, the manufacturer should increase the quality level for two products, but increase the wholesale price for the high-quality product when both the information benefit coefficient is low and the loss of personal information is low, or the information benefit coefficient is high, whereas always increase the wholesale price of the low-quality product. From the view of the product line design, the manufacturer should reduce the quality gap between the quality-differentiated products to induce consumers to share personal data. For example, Under Armour should reduce the functional gap between HOVR Phantom and HOVR Sonic. Consequently, the retailer also should decrease the selling prices of the two products.

In a word, the intuition behind these managerial insights hinges on the trade-off between the information benefit from the product quality and the loss of personal information for consumers. In this sense, our results provide guidelines for quality decisions and pricing strategy in supply chain management with consumers’ privacy concerns.

Acknowledgments. We thank the Editor-in-Chief (Prof. Kok Lay Teo), and four anonymous referees for their constructive and insightful comments, which help us significantly improve the quality of our paper. This work was supported by the National Natural Science Foundation of China (grant 72072041), the Chinese National Funding of Social Science (19BGL094), and the Guangzhou Data and Law Research Center.

Appendix.

Proof of Lemma 4.1. For give any value of product quality level and wholesale price, the retailer first solves \( \max_p \pi^N_R = (p - w) \frac{w - q}{q} \) to get the value of \( p \). We can easily obtain

\[
\frac{\partial \pi^N_R}{\partial p} = \frac{q + w - 2p}{q} = 0.
\]

Clearly, the unique solution of the selling price is given by \( p^* = \frac{q + w}{2} \). According to this, we next obtain optimal wholesale price for the product. Therefore, the
PRICING AND QUALITY DECISIONS IN A SUPPLY CHAIN WITH...

manufacturer solves
\[ \max_w \pi_M^N(w) = (w - q^2)D^N(p^*, q) = \frac{(w - q^2)(q - w)}{2q}, \]
we can easily obtain
\[ \frac{\partial \pi_M^N}{\partial w} = \frac{q + q^2 - 2w}{2q} = 0. \]
Clearly, the unique solution of the wholesale price is given by \( w^* = \frac{q(1+q)}{2}. \) Based on the above, we then get the value of the product quality level. The manufacturer solves
\[ \max_q \pi_M^N(q) = (w^* - q^2)D^N(p^*, q) = \frac{q(q - 1)^2}{8}. \]
We can easily obtain
\[ \frac{\partial \pi_M^N}{\partial q} = \frac{(q - 1)(3q - 1)}{8} = 0. \]
The solutions of the above equation are respectively given by \( q = \frac{1}{3} \) and \( q = 1. \) However, if \( q = 1, \) we can easily observe that the payoff of the manufacturer is zero, which is not the optimal solution. Therefore, we have the optimal solutions, as shown in Lemma 4.1.

**Proof of Lemma 4.2.** For give any value of product quality level and wholesale price, the retailer first solves
\[ \max_p \pi_R^S = (p - w)\frac{q^2 - (p + c - bq)}{q} \]
to get the value of \( p. \) We can easily obtain
\[ \frac{\partial \pi_R^S}{\partial p} = \frac{q + bq + w - 2p - c}{q} = 0. \]
Clearly, the unique solution of the wholesale price is given by \( p^* = \frac{q + bq + w - c}{2}. \) According to this, we next obtain optimal wholesale price for the product. Therefore, the manufacturer solves
\[ \max_w \pi_M^S(w) = (w - q^2)D^S(p^*, q) = \frac{(w - q^2)(q - w)}{2q}, \]
we can easily obtain
\[ \frac{\partial \pi_M^S}{\partial w} = \frac{q(1 + b + q) - 2w - c}{2q} = 0. \]
Clearly, the unique solution of the wholesale price is given by \( w^* = \frac{q(1+b+q)-c}{2}. \) Based on the above, we then get the value of the product quality level. The manufacturer solves
\[ \max_q \pi_M^S(q) = (w^* - q^2)D^S(p^*, q) = \frac{[q(q - b - 1) + c]^2}{8q}. \]
We can easily obtain
\[ \frac{\partial \pi_M^S}{\partial q} = -\frac{[(b + 1 - 3q)q + c][q - (b - 1)q + c]}{8q^2} = 0. \]
The solutions of the above equation are respectively given by \( q = \frac{1+b-\sqrt{-4c+(1+b)^2}}{2}, \)
\( q = \frac{1+b+\sqrt{-4c+(1+b)^2}}{2}, \)
\( q = \frac{1+b+\sqrt{12c+(1+b)^2}}{6}, \)
and \( q = \frac{1+b+\sqrt{12c+(1+b)^2}}{6}. \) First, \( q = \frac{1+b-\sqrt{-4c+(1+b)^2}}{2} < 0 \) is not an optimal solution. In addition, if \( q = \frac{1+b+\sqrt{12c+(1+b)^2}}{2} \)
or \( q = \frac{1+b+\sqrt{-4c+(1+b)^2}}{2}, \) then we can easily have the payoff of manufacturer equals
zero, which is also not the optimal solution. Because \( \frac{\partial^2 \pi_H^*}{\partial q^2} \bigg|_{q=1} \leq 0 \), which is the unique optimal solution. Therefore, we have the optimal solutions, as shown in Lemma 4.2. The value of \( F_1(b, c) \) is \((-c + 1/6b(1 + b + \sqrt{12c + (1 + b)^2}) + 1/2(c + 1/6(-1 - b - \sqrt{12c + (1 + b)^2}) - 1/6b(1 + b + \sqrt{12c + (1 + b)^2}) + 1/2(c - 1/6(b + \sqrt{12c + (1 + b)^2})(1 + b + 1/6(1 + b + \sqrt{12c + (1 + b)^2}))) (1 - 1/(1 + b + \sqrt{12c + (1 + b)^2})6(c - 1/6b(1 + b + \sqrt{12c + (1 + b)^2}) + 1/2(-c + 1/6(b + \sqrt{12c + (1 + b)^2}) + 1/2(c - 1/6(b + \sqrt{12c + (1 + b)^2})(1 + b + 1/6(1 + b + \sqrt{12c + (1 + b)^2}))) + 1/6b(1 + b + \sqrt{12c + (1 + b)^2})2(1/2 - 1/(1 + b + \sqrt{12c + (1 + b)^2})2(1/2 - 1/(1 + b + \sqrt{12c + (1 + b)^2}) + 1/2(-c + 1/6b(1 + b + \sqrt{12c + (1 + b)^2}) + 1/2(-c + 1/6(1 + b + \sqrt{12c + (1 + b)^2})(1 + b + 1/6(1 + b + \sqrt{12c + (1 + b)^2}))2)). □

Proof of Proposition 1. By Lemma 4.2, we have
\[
\begin{align*}
\frac{\partial \pi_H^*}{\partial c} &= \frac{5+5b-4A}{6A}, \quad \frac{\partial \pi_W^*}{\partial c} = \frac{2+2b-A}{3A}, \quad \frac{\partial D^S}{\partial c} = \frac{1}{A}, \quad \frac{\partial D^S}{\partial w} = -\frac{1}{A}; \\
\frac{\partial \pi_H^*}{\partial t} &= \frac{5}{36}(6c+(1+b)(1+b+A)), \quad \frac{\partial \pi_W^*}{\partial t} = \frac{1}{12}(1+2b+A); \\
\frac{\partial \pi_H^*}{\partial b} &= \frac{5}{18A}, \quad \frac{\partial \pi_W^*}{\partial b} = \frac{1}{6A}; \\
\frac{\partial \pi_H^*}{\partial \pi_H^*} &= \frac{5}{36}(-12c + (1+b)(1+b+A)); \\
\frac{\partial \pi_W^*}{\partial \pi_H^*} &= \frac{1}{12}(-12c + (1+b)(1+b+A)); \\
\frac{\partial \pi_H^*}{\partial \pi_W^*} &= \frac{1}{12}(-12c + (1+b)(1+b+A)).
\end{align*}
\]

As we explained in Section 3, we assume that \( c \leq \frac{1+2b+b^2}{4} \), then the above results can be easily obtained. □

Proof of Theorem 4.3. By Lemma 4.1 and Lemma 4.2, we have
\[
\begin{align*}
p_{N^*}^S - p_{N^*}^W &= -\frac{2c}{\sqrt{N}} + \frac{5}{36}[1 - b + b^2 + A + b(2 + A)], \\
w_{N^*}^S - w_{N^*}^W &= \frac{1}{3}[1 - 3c + 2b + b^2 + A + bA], \\
q_{N^*}^S - q_{N^*}^W &= \frac{1}{6}(-1 + b + A), \\
\pi_{R^*}^S - \pi_{R^*}^N &= \frac{72c^2+6(3+6b)(1+b)+6b(1+b+2A)}{108(1+b+A)}, \\
\pi_{M^*}^S - \pi_{M^*}^N &= \frac{72c^2+6(3+6b)(1+b)+6b(1+b+2A)}{54(1+b+A)}, \\
C S_{N^*}^S - C S_{N^*}^W &= -\frac{1+12c(1-b)(1+b)}{216(1+b+A)}.
\end{align*}
\]

where \( A = \sqrt{(1+b)^2+12c} \). We can get unique solutions solving \( \pi_{R^*}^S - \pi_{R^*}^N = 0, \pi_{M^*}^S - \pi_{M^*}^N = 0, \) and \( C S_{N^*}^S - C S_{N^*}^W = 0 \).

Proof of Lemma 5.1. \( C S_{N^*}^S = \frac{-1+12c(1-b)(1+b)}{216(1+b+A)} \). The proof is the same as Lemma 4.2, thus we omit it here.

Proof of Lemma 5.2. For give any value of product quality level and wholesale price, the retailer first solves \( \max_{p_H, p_L} \pi_{R^*}^S (p_H, p_L) = (p_H - w_H) D_N^H + (p_L - w_L) D_N^L \) where \( D_N^H = 1 - \frac{p_H - p_L}{q_H - q_L} \) and \( D_N^L = \frac{p_H - p_L}{q_H - q_L} - \frac{p_L}{q_L} \), we have that
\[
\begin{align*}
\frac{\partial \pi_{R^*}^S}{\partial p_H} &= -\frac{2p_H+2p_L+q_H-q_L+w_H-w_L}{q_H-q_L}, \\
\frac{\partial \pi_{R^*}^S}{\partial p_L} &= -\frac{2p_Lq_H+2p_Hq_L-w_H-w_L}{(q_H-q_L)q_L}, \\
\frac{\partial \pi_{R^*}^S}{\partial q_H} &= 0, \\
\frac{\partial \pi_{R^*}^S}{\partial q_L} &= 0.
\end{align*}
\]
where the Hessian is \( H_1 = \)

\[
\begin{pmatrix}
-\frac{2}{q_H+q_L} & -\frac{2}{q_H+q_L} \\
\frac{2}{q_H+q_L} & \frac{2}{q_H+q_L}
\end{pmatrix}
\]

It needs to meet a condition: \( \frac{2}{q_H+q_L} < 0 \) and \(|H_1| = \frac{4}{(q_H+q_L)^2} > 0 \). The unique solutions of the above equation are respectively given by \( p_H^* = \frac{1}{2}(q_H + w_H) \) and \( p_L^* = \frac{1}{2}(q_L + w_L) \). Next, for given \( q_H \) and \( q_L \), the manufacturer solves

\[
\max_{w_H,w_L} \pi_M^N(w_H, w_L) = (w_H - q_H^2)D_H^N + (w_L - q_L^2)D_L^N,
\]

where \( D_H^N = \frac{q_H w_H - q_H w_L + w_L}{2(q_H - q_L)q_L} \) and \( D_L^N = \frac{q_L w_H - q_H w_L + w_L}{2(q_H - q_L)q_L} \), and then we have that

\[
\begin{aligned}
\frac{\partial \pi_M^N}{\partial w_H} &= q_H + q_H^2 - q_L(1+q_L)-2w_H+2w_L = 0, \\
\frac{\partial \pi_M^N}{\partial w_L} &= q_H^2 q_L - q_H q_L^2 - 2w_H w_L + 2q_H w_L = 0,
\end{aligned}
\]

where the Hessian is \( H_2 = \)

\[
\begin{pmatrix}
-\frac{1}{q_H+q_L} & -\frac{1}{q_H+q_L} \\
\frac{1}{q_H+q_L} & \frac{1}{q_H+q_L}
\end{pmatrix}
\]

It needs to meet a condition: \( \frac{1}{q_H+q_L} < 0 \) and \(|H_2| = \frac{1}{q_H q_L - q_L^2} > 0 \). At this time, we also have that \( w_H^* = \frac{1}{2}(q_H + q_H^2) \) and \( w_L^* = \frac{1}{2}(q_L + q_L^2) \) by solving the above equation. Next, according to this, the manufacturer solves

\[
\max_{q_H,q_L} \pi_M^N(q_H, q_L) = (w_H - q_H^2)D_H^N + (w_L - q_L^2)D_L^N,
\]

where \( D_H^N = \frac{1}{4}(1 - q_H - q_L) \) and \( D_L^N = \frac{1}{4} q_L^2 \). The first-order optimality condition is

\[
\begin{aligned}
\frac{\partial \pi_M^N}{\partial q_H} &= \frac{1}{2}(-1 + 3q_H - q_L)(-1 + q_H + q_L) = 0, \\
\frac{\partial \pi_M^N}{\partial q_L} &= \frac{1}{2}(q_H^2 - 2q_H q_L) = 0,
\end{aligned}
\]

where the Hessian is \( H_3 = \)

\[
\begin{pmatrix}
\frac{1}{2}(-2 + 3q_H + q_L) & \frac{1}{2}(q_H - q_L) \\
\frac{1}{2}(q_H - q_L) & -\frac{2q_H}{q_H^2}
\end{pmatrix}
\]

Also, it needs to meet a condition: \( \frac{1}{4}(-2 + 3q_H + q_L) < 0 \) and \(|H_3| = \frac{-4q_H^2 - q_L^2 + q_H(2+q_L)}{16} > 0 \). At this time, solving the above equation and condition, we have the optimal solutions as shown in Lemma 5.2.

**Proof of Lemma 5.3.** For give any value of product quality level and wholesale price, the retailer first solves \( \max_{p_H, p_L} \pi_R^S(p_H, p_L) = (p_H - w_H)D_H^S + (p_L - w_L)D_L^S \) where \( D_H^S = 1 - \frac{\rho_H - \rho_L - \beta_H + \beta_L}{q_H - q_L} \) and \( D_L^S = \frac{\rho_H - \rho_L - \beta_H + \beta_L}{q_H - q_L} - \frac{\rho_L}{q_L} \). Clearly, we have that

\[
\begin{aligned}
\frac{\partial \pi_R^S}{\partial p_H} &= \frac{p_H q_H + (1+b)q_H - (1+b)q_L + w_H - w_L}{q_H - q_L} = 0, \\
\frac{\partial \pi_R^S}{\partial p_L} &= \frac{2p_L q_H - 2p_L q_L + (q_H - q_L)q_H w_H - q_H w_L}{(-q_H + q_L)q_L} = 0,
\end{aligned}
\]

where the Hessian is \( H_1 = \)

\[
\begin{pmatrix}
-\frac{2}{q_H+q_L} & -\frac{2}{q_H+q_L} \\
\frac{2}{q_H+q_L} & \frac{2}{q_H+q_L}
\end{pmatrix}
\]
It needs to meet a condition: $-\frac{2}{q_H + q_L} < 0$ and $|H_1| = \frac{4}{(q_H - q_L)q_L} > 0$. Next, we have that $p^*_H = \frac{1}{2}(q_H + w_H + b q_H - c)$ and $p^*_L = \frac{1}{2}(q_L + w_L + b q_L - c)$ according to the above equation and condition. Next, the manufacturer solves

$$\max_{w_H, w_L} \pi^S_M(w_H, w_L) = (w_H - q_H^2)D_H^S + (w_L - q_L^2)D_L^S,$$

where $D_H^S = \frac{q_H + b q_H - q_L - b q_L - w_L}{2q_H - 2q_L}$ and $D_L^S = -\frac{c q_H - c q_L - q_H w_H + q_H w_L}{2(q_H - q_L)q_L}$, which is also a concave maximization. The first-order optimality condition is

$$\left\{ \begin{array}{l}
\frac{\partial \pi^S_M}{\partial w_H} = \frac{(1 + b) q_H + q_H^2 - q_L(1 + b + q_L) - 3 w_H + 2 w_L}{2 q_H - 2 q_L} = 0, \\
\frac{\partial \pi^S_M}{\partial w_L} = -\frac{c q_H - c q_L - q_H w_H + q_H w_L}{2(q_H - q_L)q_L} = 0,
\end{array} \right.$$  

where the Hessian is $H_2 = \frac{1}{-q_H + q_L} - \frac{1}{q_H - q_L}$. It needs to meet a condition: $-\frac{1}{q_H + q_L} < 0$ and $|H_2| = \frac{1}{q_H q_L - q_L^2} > 0$. At this time, solving the above equation and condition, we can obtain $w_H^* = \frac{1}{2} q_H (1 + b + q_H - c)$ and $w_L^* = \frac{1}{2} q_L (1 + b + q_L - c)$. Next, we derive the manufacturer’s optimal quality. The manufacturer solves the following optimization problem:

$$\max_{q_H, q_L} \pi^S_M(q_H, q_L) = (w_H - q_H^2)D_H^S + (w_L - q_L^2)D_L^S,$$

where $D_H^S = \frac{1 + b - q_H - q_L}{4}$ and $D_L^S = \frac{1}{4} q_H - \frac{c}{q_L}$. The first-order optimality condition is

$$\left\{ \begin{array}{l}
\frac{\partial \pi^S_M}{\partial q_H} = \frac{1}{8}(1 + b - 3 q_H + q_L)(1 + b - q_H + q_L) = 0, \\
\frac{\partial \pi^S_M}{\partial q_L} = \frac{1}{8}(2 c + q_H^2 - 2 q_H q_L - q_L^2) = 0,
\end{array} \right.$$

where the Hessian is $H_3 = \left( \begin{array}{ccc} \frac{1}{4}(-2 - 2 b + 3 q_H + q_L) & \frac{1}{4}(q_H - q_L) & \frac{1}{4}(-q_H + \frac{c^2}{q_L}) \\ \frac{1}{4}(q_H - q_L) & \frac{1}{4}(q_H - q_L) & \frac{1}{4}(-q_H + \frac{c^2}{q_L}) \end{array} \right)$. Also, it needs to meet a condition: $\frac{1}{4}(-2 - 2 b + 3 q_H + q_L) < 0$ and

$$|H_3| = \frac{c^2(-2 - 2 b + 3 q_H + q_L) + q_L^2[q_H(-4 q_H^2 - q_H^2 + q_H(2 + 2 b + q_L))]}{16} > 0.$$  

At this time, solving the above equation and condition, we have the optimal solutions as shown in Lemma 5.3. Notably, because the expression of $F_2(b, c)$ is too long, we omitted here, please contact us if necessary. \hfill \Box

**Proof of Proposition 3.** By Lemma 4.2, we have

$$\left\{ \begin{array}{l}
\frac{\partial \pi^S_M}{\partial c} = \frac{5 + b + 4 q_H - 4 A}{6 A}, \quad \frac{\partial \pi^S_M}{\partial q_H} = \frac{2 + b - A}{A}, \quad \frac{\partial D_H^S}{\partial q_H} = \frac{1}{X}, \quad \frac{\partial D_L^S}{\partial q_L} = -\frac{1}{X}, \\
\frac{\partial \pi^S_M}{\partial q_L} = \frac{1}{6} (-2 - 2 b + A), \quad \frac{\partial D_H^S}{\partial q_L} = \frac{1}{12} (-2 - 2 b + A), \\
\frac{\partial \pi^S_M}{\partial A} = -\frac{2 - 2 b + A}{24}.
\end{array} \right.$$
where $A$

By Lemma 5.2 and Lemma 5.3, we have

\[ \pi \leq \frac{1+2b+b^2}{4}, \]

As we explained in Section 3, we assume that $c \leq \frac{1+2b+b^2}{4}$, then the above results can be easily obtained.

**Proof of Theorem 5.4.** By Lemma 5.2 and Lemma 5.3, we have

\[
\begin{align*}
\frac{\partial p_{S}^*}{\partial p_{N}^*} &= \frac{5[6c+(1+b)(1+b+A)]}{15[A]}, \\
\frac{\partial p_{R}^*}{\partial p_{N}^*} &= \frac{1}{2}[1+\frac{1+b}{A}], \\
\frac{\partial w_{L}^*}{\partial p_{N}^*} &= \frac{1}{36}[-12c+(1+b)(1+b+A)], \\
\frac{\partial w_{R}^*}{\partial p_{N}^*} &= \frac{1}{144}[-12c+(1+b)(1+b+A)], \\
\frac{\partial \pi_{S}^*}{\partial p_{N}^*} &= \frac{1}{10}[10 + A], \\
\frac{\partial \pi_{R}^*}{\partial p_{N}^*} &= \frac{1}{10}[10 - A].
\end{align*}
\]

where $A = \sqrt{(1+b)^2 + 60c}$. We can get unique solutions by solving $\pi_{S}^* - \pi_{N}^* = 0$, $\pi_{M}^* - \pi_{N}^* = 0$, and $CS_{S}^* - CS_{N}^* = 0$. 

**REFERENCES**

[1] A. Acquisti, C. Taylor and L. Wagman, The economics of privacy, *Social Science Electronic Publishing*, **54** (2016), 442–492.

[2] S. Buehler, A. Schmutzler and M. A. Benz, Infrastructure quality in deregulated industries: Is there an underinvestment problem?, *International Journal of Industrial Organization*, **22** (2004), 253–267.

[3] R. Casadesus-Masanell and A. Hervas-Drane, Competing with privacy, *Management Science*, **61** (2015), 229–246.

[4] J.-H. Cheah, X.-J. Lim, H. Ting, Y. Liu and S. Quach, Are privacy concerns still relevant? revisiting consumer behaviour in omnichannel retailing, *Journal of Retailing and Consumer Services*, (2020), 102242.

[5] J. Chen, L. Liang, D. Q. Yao and S. Sun, Price and quality decisions in dual-channel supply chains, *European J. Oper. Res.*, **259** (2017), 935–948.

[6] V. Conitzer, C. R. Taylor and L. Wagman, Hide and seek: Costly consumer privacy in a market with repeat purchases, *Marketing Science*, **31** (2012), 277–292.

[7] C. Conti and P. Reverberi, Price discrimination and product quality under opt-in privacy regulation, *Information Economics and Policy*, **55** (2021), 100912.

[8] Q. Cui, Quality investment, and the contract manufacturer’s encroachment, *European J. Oper. Res.*, **279** (2019), 404–418.

[9] K. Degirmenci, Mobile users’ information privacy concerns and the role of app permission requests, *International Journal of Information Management*, **50** (2020), 261–272.

[10] Desai and S. Preyas, Quality segmentation in spatial markets: When does cannibalization affect product line design?, *Marketing Science*, **20** (2001), 265–283.

[11] S.-Z. Dong, L. Yang, B. Ding, C.-H. Wu and X.-F. Shao, Pricing strategy with customers’ privacy concerns in smart-x systems, *Enterprise Information Systems*, (2020), 1–27.

[12] F. Gao and X. Su, Omnichannel retail operations with buy-online-and-pick-up-in-store, *Management Science*, **63** (2016), 2478–2492.

[13] A. Ghose, B. Li and S. Liu, Nudging mobile customers with real-time social dynamics, *Social Science Electronic Publishing*.
[14] A. Goli, H. Khademi-Zare, R. Tavakkoli-Moghaddam, A. Sadeghieh, M. Sasanian and R. M. Kordestanizadeh, An integrated approach based on artificial intelligence and novel meta-heuristic algorithms to predict demand for dairy products: A case study, *Network: Computation in Neural Systems*, 32 (2021), 1–35.

[15] A. Goli and B. Malmir, A covering tour approach for disaster relief locating and routing with fuzzy demand, *International Journal of Intelligent Transportation Systems Research*, 18 (2019), 140–152.

[16] A. Goli, E. B. Tirkolaee and N. S. Aydin, Fuzzy integrated cell formation and production scheduling considering automated guided vehicles and human factors, *IEEE Transactions on Fuzzy Systems*, 29 (2021), 3686–3695.

[17] A. Goli, H. K. Zare, R. Tavakkoli-Moghaddam and A. Sadeghieh, Application of robust optimization for a product portfolio problem using an invasive weed optimization algorithm, *Numer. Algebra Control Optim.*, 9 (2019), 187–209.

[18] A. Ha, X. Long and J. Nasiry, Quality in supply chain encroachment, *Manufacturing & Service Operations Management*, 18 (2016), 280–298.

[19] Y. He, Q. Xu, B. Xu and P. Wu, Supply chain coordination in quality improvement with reference effects, *Journal of the Operational Research Society*, 67 (2016), 1158–1168.

[20] J. Jaisingh, J. Barron, S. Mehta and A. Chaturvedi, Privacy and pricing personal information, *European J. Oper. Res.*, 187 (2008), 857–870.

[21] A. Jeuland and S. Shugan, Managing channel profits, *Marketing Science*, 2 (1988), 239–272.

[22] E. Kim and B. Lee, E-service quality competition through personalization under consumer privacy concerns, *Electronic Commerce Research and Applications*, 8 (2009), 182–190.

[23] B. Koh, S. Raghunathan and B. R. Nault, Is voluntary profiling welfare enhancing?, *MIS Quarterly*, 41 (2017), 23–41.

[24] X. Lin, Y. W. Zhou and R. Hou, Impact of a “buy-online-and-pickup-in-store” channel on price and quality decisions in a supply chain, *European J. Oper. Res.*, 294 (2021), 922–935.

[25] Y. Liu, H. Shi and N. C. Petruzzi, Optimal quality and quantity provisions for centralized vs. decentralized distribution: Market size uncertainty effects, *European J. Oper. Res.*, 265 (2018), 1144–1158.

[26] R. Lotfi, B. Kargar, S. H. Hoseini, S. Nazari, S. Safavi and G. W. Weber, Resilience and sustainable supply chain network design by considering renewable energy, *International Journal of Energy Research*, 45 (2021), 17749–17766.

[27] R. Lotfi, N. Mardani and G.-W. Weber, Robust bi-level programming for renewable energy location, *International Journal of Energy Research*, 45 (2021), 7521–7534.

[28] R. Lotfi, M. Nayeri, S. M. Sajadifar and N. Mardani, Determination of start times and ordering plans for two-period projects with interdependent demand in project-oriented organizations: A case study on molding industry, *Journal of Project Management*, 2 (2017), 119–142.

[29] R. Lotfi, Y. Zare Mehrjerdi, M. Fishevaee, A. Sadegheh and G.-W. Weber, A robust optimization model for sustainable and resilient closed-loop supply chain network design considering conditional value at risk, *Numer. Algebra Control Optim.*, 11 (2021), 221–253.

[30] K. S. Moorthy, Market segmentation, self-selection, and product line design, *Marketing Science*, 3 (1984), 288–307.

[31] M. Mussa and S. Rosen, Monopoly and product quality, *J. Econom. Theory*, 18 (1978), 301–317.

[32] N. J. Ogbuke, Y. Y. Yusuf, K. Dharma and B. A. Mercangoz, Big data supply chain analytics: Ethical, privacy and security challenges posed to business, industries and society, *Production Planning & Control*, (2020), 1–15.

[33] E. Özceylan, C. Çetinkaya, N. Demirel and O. Sabriioğlu, Impacts of additive manufacturing on supply chain flow: A simulation approach in healthcare industry, *Logistics*, 2 (2018), 1.

[34] S. M. Pahlevan, S. Hosseini and A. Goli, Sustainable supply chain network design using products’ life cycle in the aluminum industry, *Environmental Science and Pollution Research*, (2021), 1–25.

[35] M. Rodrigo, S. Z. Willfried and V. Tommaso, The value of personal information in online markets with endogenous privacy, *Management Science*, 65 (2019), 1342–1362.

[36] H. Shi, Y. Liu and N. C. Petruzzi, Consumer heterogeneity, product quality, and distribution channels, *Management Science*, 59 (2013), 1162–1176.

[37] Y. Song, T. Fan, Y. Tang and F. Zou, Quality information acquisition and ordering decisions with risk aversion, *International Journal of Production Research*, 59 (2021), 6864–6880.
[38] G. J. Stigler, The law and economics of privacy – an introduction to privacy in economics and politics, *Journal of Legal Studies*, 9 (1980), 623–644.

[39] S. Wang, Q. Hu and W. Liu, Price and quality-based competition and channel structure with consumer loyalty, *European J. Oper. Res.*, 262 (2017), 563–574.

[40] X. Xu, Optimal price and product quality decisions in a distribution channel, *Management Science*, 55 (2009), 1347–1352.

[41] Y. Yu, Y. Wang and Y. Liu, Product quality and quantity with responsive pricing, *International Journal of Production Research*, 59 (2021), 7160–7178.

[42] Q. Zhang, W. Tang, G. Zaccour and J. Zhang, Should a manufacturer give up pricing power in a vertical information-sharing channel?, *European J. Oper. Res.*, 276 (2019), 910–928.

[43] Z. Zhang, K. Joseph and R. Subramaniam, Probabilistic selling in quality-differentiated markets, *Management Science*, 61 (2015), 1959–1977.

Received July 2021; 1st revision October 2021; 2nd revision November 2021; early access January 2022.

E-mail address: zhaoyou728@outlook.com
E-mail address: 1265255938@qq.com
E-mail address: chenjianxin403@163.com
E-mail address: hour@gdut.edu.cn