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Pricing and coordination with consideration of piracy for digital goods in supply chains

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ABSTRACT

Sales of digital goods via traditional channels are affected by those on digital channels, and thus a competitive relationship often exists. In addition, due to the ease of piracy, digital goods may suffer from a fall in demand, which intensifies competition. This study considers a single supplier who sells digital goods, which may be pirated, to customers through two independent and different retail channels, such as traditional and digital ones, which may compete with each other in terms of service and price. To consider the effects of piracy on demand, a Stackelberg game is utilized to determine the optimal gain-sharing ratio and the equilibrium prices for all channel members with an aim to maximize the profit of the entire supply chain. It is found that an increase in piracy would force retailers to compete in a smaller market, and thus lead to a decrease in profits for each channel member. Therefore, a retailer who has a greater market share and is capable of managing a lower piracy rate would gain more profits by setting a higher price.

1. Introduction

Digital goods differ from traditional ones in the characteristic of having a relatively high fixed cost but extremely low marginal one, meaning that the profits increase quickly as the sales volume rises (Turban et al., 2008). However, since digital goods are easy to copy and can be transmitted at low cost, this makes piracy easier and cheaper. Piracy is copying or utilizing a product without permission from the party who owns the copyright, and it often has unfavorable impacts on the wider society, even though consumers are obviously pleased to obtain the product for free (Johnson, 1985). Yang, Wang, and Mourali (2015) investigated two forms of music piracy in schools and colleges, unauthorized downloading and sharing, in order to prevent them, while Jacobs, Heuvelman, Tan, and Peters (2012) studied downloading behavior in the context of digital movie piracy. The findings showed that the influence of any knowledge of the related laws on the expected economic outcomes is negative. Various ways to prevent piracy are proposed in the literature (Khouja & Park, 2008; Khouja & Rajagopalan, 2009; Wu & Chen, 2008), and while most studies suggested that piracy has negative effects, some considered that it may actually increase demand and thus enhances profits (Conner & Rumelt, 1991). Hsu, Wang, and Wu (2013) indicated that the government should do whatever is in its power to protect intellectual property and punish piracy, as this will motivate firms to invest in innovation. Appleyard (2015) examined a number of practical cases to propose six lessons in developing effective anti-piracy strategies. The author concludes that these could guide managers to protect existing rights and engage with new market paradigms.

Digital goods sold by different channels have different values to consumers and retailers. Consumers may prefer the physical versions of products, as it gives more value through the experience of real possession, even though they have to wait to receive these, in contrast to digital copies, which can be delivered immediately. On the other hand, offering a physical version means retailers have to bear the production, inventory, and distribution costs, and though these can be easily cut by selling the virtual version on the Internet, such an arrangement may not be satisfactory for many consumers, who may enjoy the atmosphere of a real store. In sum, while these two channels may grow the entire market, they also create dilemmas for customers and retailers. Moreover, they bring more competition to the market (Jiang & Katsamakas, 2010; Kim, Chang, & Shocker, 2000). Competition may occur for each different channel if the product is sold in different forms, and the manufacturer would therefore postpone or stagger the selling periods for different channels or sell the product only in a single one. Such practices are common in the film industry, as movies often only have online versions sold after their DVD versions have been available for a while, while some are never offered online. However, in any case the demand is usually highest when a product first becomes available on the market, and generally decreases dramatically after this initial period. Therefore,

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digital goods are now often sold by both virtual and physical channels at the same time. Different approaches may be used to avoid competition in such cases; for example, selling products only by a single channel, offering different editions of the product and bundling (Koukova, Kannan, & Ratchford, 2008), or deferring the selling times for other channels to avoid competition between two similar and substitutable products (Thorsten, Henning, Sattler, Eggers, & Houston, 2007).

As digital channels have been introduced to the market, so competition has become more intense. The traditional channel often address this by adding value, while the digital channel may reduce the price by taking advantage of its low (or zero) marginal cost to attract more consumers. This may eventually result in a price war, and make the market unprofitable for each channel member. Members in the supply chain thus have to horizontally and vertically coordinate with each other to obtain the maximum profits. Supply chain coordination has been extensively studied (Bernstein & Federgruen, 2003; Cachon, 2004; Jeuland & Shugan, 1983; Pan, Lai, Leung, & Xiao, 2010), and the coordination mechanism adopted in this context may involve various different considerations, such as a wholesale price contract (Raman et al., 2005), rebate contract (Leng & Parlar, 2010; Pasternack, 2008), revenue sharing (Cachon & Lariviere, 2005; Giannoccaro & Pontrandolfo, 2004), and quantity discount (Rhee, van der Veen, Venugopal, & Nalla, 2010). Among these, revenue-sharing coordination has been widely applied in industries which have extremely low marginal costs, such as those that sell digital products on the Internet (Foros et al., 2009). Moreover, revenue-sharing coordination, which can prevent price wars, is widely applied in the DVD rental industry (Gerchak, Cho, & Ray, 2006). It is not uncommon in practice for retailers to share their sales revenues with suppliers. Hence, it may be important for suppliers and retailers to share the profits in the supply chain, especially when demand for digital goods is affected by piracy. Moreover, some inducements may be needed to encourage each channel member to behave according to the mutual agreement, even if there is a good gain-sharing mechanism. Extensive research on the pricing strategy under such competition has been carried out (Tang & Xing, 2001; Viswanathan, 2005; Yan, Wang, & Zhou, 2010; Cai, 2010; Kogan et al., 2013; Chang and Walter, 2015), indicating the importance of coordination for such a competitive multi-channel market. Therefore, this study demonstrates how a supplier and retailers can coordinate by the use of a contractual gain-sharing mechanism, and determine the equilibrium prices and the optimal gain-sharing ratio when a digital product is sold in a supply chain under the multi-channel competition with consideration of piracy.

Conflict will always occur when new channels enter the market, resulting in double marginality and lowering the profit as a whole for the supply chain, since every channel member aims to achieve profit maximization for themselves (Yan et al., 2010; Yao & Liu, 2005). Therefore, an appropriate coordination mechanism which can be used in different situations for different overall benefits is essential. Moreover, some studies derived the equilibrium prices for channel members with coordination by considering the supply chain as a whole and aiming to maximize the overall profit. Yan and Ghose (2010) derived the Bertrand equilibrium prices in consideration of independent firms in a dual-channel competitive market. Li, Zhu, and Huang (2009) utilized a Nash equilibrium model to describe how both the manufacturer and retailer can earn more profit in cooperation. Yan (2008) analyzed the equilibrium prices for a mixed online and traditional retail channel in order to maximize profits, and suggested that a profit-sharing policy can be as an incentive to coordinate online and traditional channels to achieve overall optimization. However, it is not applicable in practice to assume that both parties would completely cooperate with each other. This study thus focuses on a supply chain in which a supplier sells digital goods that can be pirated and sold at the same time by both the traditional channel with physical carriers, and the virtual channel with digital carriers. This supplier does not directly enter the market, but instead sells the digital product through another two independent retailers who sell it in different forms, which can be mutually substituted under service and price competition. Different proportions of revenue sharing are adopted for different retailers in this study to obtain the maximum profit for each channel member.

The rest of this paper is organized as follows: section two describes the research problem and presents the notations adopted in the proposed model. Section three shows the research framework and the model formulation regarding the research problem, while section four performs analytical and numerical analyses to obtain the managerial implications. Finally, section five gives the conclusion and states the contributions of this work and suggestions for future studies.

2. Competition of digital goods on dual channels

The schema used in this study is extended from Yan and Ghose's work (2010) and considers a single supplier that provides similar and substitutable digital goods to customers by two different retailing channels which offer different services and prices, and analyses how the supplier and the two retailers can coordinate by the use of a revenue-sharing mechanism to set their prices with an aim of maximizing the profits of the supply chain as a whole. Here, the digital goods are defined as those products that can be digitalized. For example, the contents of books, DVDs, CDs and professional software can be digitalized and sold on the Internet, while they can also be sold at physical stores.

Fig. 1 shows the framework of the research model, with a powerful supplier and two asymmetric retailers considered in the system. The supplier sells digital goods in two different forms through a traditional physical channel and an Internet virtual channel, respectively, and the two retailers then sell the product to consumers not only at different prices, but also with different services, including promotion, exhibition of products, advertisements, the time needed to obtain the product, and the shopping atmosphere. The supplier is the Stackelberg leader who declares wholesale prices and the revenue-sharing rule to the retailers as a coordination mechanism. The retailers select their price and service level independently, a Nash equilibrium is established, and profits are realized. The customers will transfer between the two market channels due to the retailers' competition. Moreover, the influence of piracy is considered in the framework, and the elasticity and cross-elasticity of price are also measured in this study.

The notations used in this study are summarized in Table 1.

Suppose that D_r is the demand faced by the traditional market channel, and γ_r is its corresponding piracy rate, while D_d is the demand faced by the digital market channel, and γ_d is its corresponding piracy rate. Compared with the virtual channel, since the traditional physical channel usually cannot fulfill a large demand when the product is first introduced to the market, due to the high carrier cost and insufficient inventory space, consumers would have to wait a long time for delivery. In such cases, unsatisfied consumers may not be willing to wait, and thus turn to purchase the product from the digital market channel, even though the physical channel can often provide a more comfortable shopping atmosphere. S_r denotes the service level provided by the retailer of traditional market channel. Compared with the physical channel, the product may have a late launching time or even not be available via the digital channel. In such cases, consumers may turn to purchase the product from the retailer of the traditional market channel. S_d denotes the service level provided by the digital channel, and $S_r \geq S_d$ is assumed in this study. The assumption indicates the traditional retailer's service level is better than the online retailer's. It is reasonable in practice that a customer is willing to pay a higher price to buy a product from a traditional retailer. Because they expect to get a higher level of service.

LF_s denotes the supplier's expense for purchasing the copyright from the product creator, and some royalty may also need to be paid to the product creator for each sold product. Suppose that W_r and W_d denote the marginal costs that the supplier charges the traditional and digital channels, respectively, which include the cost of the royalty paid to

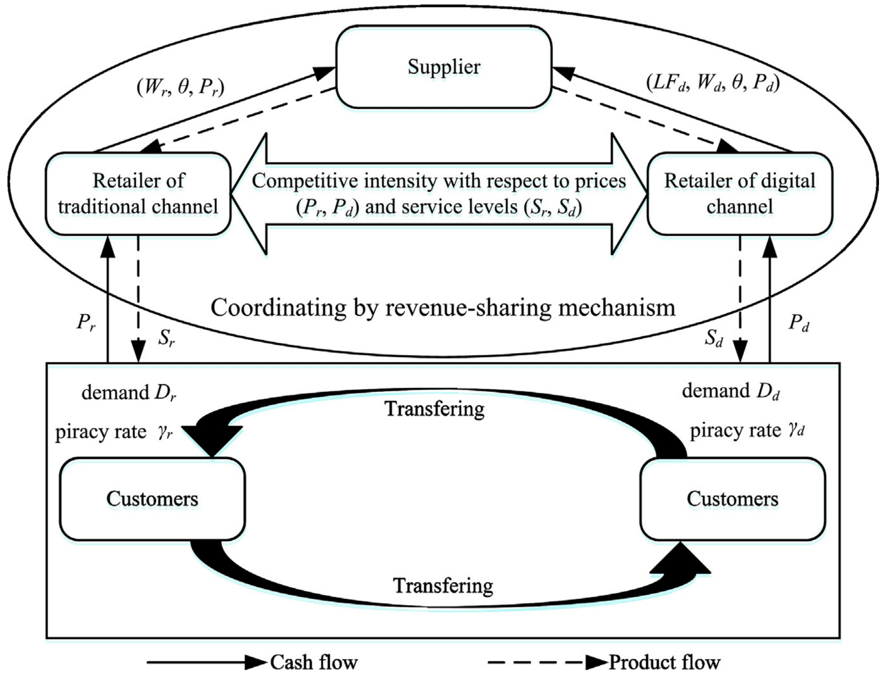

Fig. 1. The framework of the research model.

the product creator and the production cost of the product. Since the physical carriers use with the traditional retailing channel are relatively costly, the unit cost of the traditional channel is higher, i.e., $W_r \geq W_d$. As for the traditional retailer, the total cost is TC_r which includes the cost of obtaining the product and the service cost for value-added activities. On the other hand, the total cost of the online retailer is TC_d, which includes the royalty expenses, the purchasing cost of the product, and the service cost of value-added activities. Neither channel is dominant in terms of cost, and the competitive advantage depends on how the channel members manage their costs to obtain the product and offer the corresponding service.

In general, the supplier in a supply chain is often very powerful, while retailers can only determine their retail prices according to the supplier's pricing strategy and their conjectures of other retailers' prices. Therefore, in this study, the vertical coordination between the supplier and retailers is viewed to act as a Stackelberg game in which the supplier plays a role as a leader, and the two retailers act as followers. However, the horizontal competition indicates that the two retailers would guess each other's possible retail price, and thus determine their own based on this at the same time. In other words, the players of this Stackelberg game are a leader (supplier) and two followers (retailers), and the game theoretic model can be solved to achieve a Nash equilibrium where the two retailers independently set their prices with specific service levels under a proportion of revenue sharing offered by the supplier.

The coordination mechanism is based on the contractual agreement between the supplier and retailers. Suppose that a retailer initially obtains the product at a wholesale price, and then shares a proportion of revenue θ, $0<\theta<1$, with the supplier as each product is sold. In considering the proportion of revenue-sharing, since price is a major concern for consumers when purchasing the product, the retailer with the lower revenue-sharing proportion would have more price advantage if different proportions are offered by the supplier. Therefore, with consideration of fairness, the two retailers and supplier should all agree on a specific revenue-sharing proportion after negotiation. With regard to the determination of the wholesale price for the supplier, Cachon and Lariviere (2005) stated that since the revenue-sharing mechanism would result in less profit for retailers in a decentralized supply chain than for retailers in a centralized one, the supplier thus has to sell the product with a price that is lower than the cost in order for revenue-sharing coordination with retailers to succeed, and such a concept was adopted by Blockbuster to coordinate with its suppliers. In this study, the product's wholesale price is adjustable, and depends on whether the retailer is willing to share more revenue with the supplier. Therefore, the supplier's wholesale price to the traditional retailer is set as $(1-\theta^2)W_r$, which is the unit cost for obtaining the product for the traditional retailer, and this decreases as the revenue-sharing proportion θ increases. Besides, the traditional retailer would sell the product at the unit price P_r to consumers in a physical form, while the online retailer would sell the product to consumers at price P_d for a single download. Therefore, considering the revenue sharing from the traditional retailer, the supplier will increase the revenue $(1-\theta^2)D_rW_r+\theta D_rP_r$ when the traditional retailer sells a product. With regard to the traditional retailer, the marginal revenue of the supplier is equal to the marginal cost of the traditional retailer, minus the service cost. Moreover, LF_d denotes the fixed charge for copyright that the digital channel pays to the supplier, which is assumed to be exogenous and has already been set by the market for the digital goods. $LF_s \geq LF_d$ is assumed in this study. This is because

Table 1
Notations and definitions used in this study.

D_i	The actual demand faced by channel i, where $i=d$ or r (d: digital channel; r: traditional channel)
D_i'	The potential demand faced by channel i with consideration of piracy, where $i=d$ or r (d: digital channel; r: traditional channel)
A	The total market potential
α	The market share of the traditional channel
b_j	The demand sensitivity to j, where $j=p$ or s (p: price; s: service level)
c_i	The demand competitive intensity for j ($j=p,s$)
S_i	The service level of channel i ($i=d,r$)
P_i	The retail price of channel i ($i=d,r$)
θ	The proportion of revenue-sharing
γ_i	The piracy rate of channel i ($i=d,r$)
η_i	The factor of service cost for channel i ($i=d,r$)
π_s	The supplier's profit
π_i	The profit of channel i ($i=d,r$)
W_i	The wholesale price of channel i set by the supplier ($i=d,r$)
LF_d	The royalty charge for the online retailer
LF_s	The fixed cost of the supplier to obtain the product
TC_i	The total cost of the retailer i ($i=d,r$)

the fixed charge of the supplier to obtain the product's copyright should be more than the royalty charge for transferring the copyright to the online retailer. Otherwise, the online retailer will prefer to buy the copyright directly from the digital content provider if the supplier charges a fee that is more than that asked by the provider ($LF_s < LF_d$). Likewise, $(1-\theta^2)W_d$ denotes the unit cost for the digital channel. Accordingly, considering the royalty revenue from the online retailer, the supplier's revenue from the online retailer will be $(1-\theta^2)D_dW_d + \theta D_dP_d + LF_d$.

Based on the aforementioned discussion, the assumptions in this study are stated as follows:

(1) The supplier acts as a leader in the Stackelberg game, while the two retailers are followers with the same status.
(2) The two retailers and the supplier share symmetric information with each other, and consumers have complete information about these two channels.
(3) The two retailers compete in a market for the digital product, which can be pirated, and the demand is deterministic. The levels of price and service are dependent. Unsatisfied consumers in one channel would turn to purchase the product from the other one.
(4) The coordination mechanism depends on the contractual agreement with a proportion of revenue-sharing θ, and the value must be between 0 and 1. Besides, the supplier's wholesale prices for the traditional and digital retailers are assumed as $(1-\theta^2)W_r$ and $(1-\theta^2)W_d$, respectively.
(5) The service quality levels between the traditional and online retailers are assumed as $S_r \geq S_d$. The fixed charge for royalties between the supplier and online retailer are assumed as $LF_s \geq LF_d$.

In short, this study utilizes a Stackelberg game in which the supplier acts as a leader who can decide the same proportion of revenue-sharing and different wholesale prices with respect to the two retailers; while the two retailers act as followers who would determine their respective retail prices according to the supplier's decision and their conjectures about each other's possible response price. Note that consumers do not prefer either of these two channels, and that unsatisfied ones would switch to the other. Moreover, in general, the members of channels can benefit from the revenue-sharing mechanism, and the supplier can also use this mechanism to inspire the retailers to promote the products. Accordingly, with the use of an effective coordination mechanism, channel members can reasonably share the profit and thus enhance the performance of the supply chain as a whole. However, if there are no revenue-sharing or other coordination mechanisms between them, the supplier would raise the wholesale price to ensure its own revenue increased, although this would cause conflict between the supplier and retailers. Therefore, coordination can prevent or mitigate competition and bargaining in vertical chains to achieve a win-win situation. In other words, this study focuses on the optimization of the whole supply chain with equilibrium prices. In this study, the equilibrium prices can be obtained with the aim of maximizing the members' individual profit by using the backward derivation approach. The profits of the supplier and two retailers are first formulated, and the retailers' (i.e., followers) response decisions can be evaluated as the equilibrium response retail prices, which can then be substituted into the supplier's profit to obtain the supplier's optimal strategy (i.e., the optimal proportion of revenue sharing). Finally, the optimal equilibrium retail prices are obtained by substituting the supplier's optimal strategy into the retailers' profits. Therefore, the optimal strategy after supply chain coordination consists of the proportion of revenue sharing that both the supplier and retailers agree on, and the equilibrium retail prices of the two retailers.

3. The optimal equilibrium pricing and revenue-sharing strategies

Suppose that the initial demand (i.e., market potential) of the market as a whole is a if the two channel retailers set their prices at zero and offer no service at all. Suppose that the market share of the traditional channel is α, the base demand for both traditional and online retailers would thus be αa and $(1-\alpha)a$, respectively, where $0 \leq \alpha \leq 1$. However, when the price and service level vary for the two channels, the demand would change. Suppose that b_p and b_s denote the price and service sensitivity to demand, respectively, and c_p and c_s denote the retailers' competitive intensity with respect to price and service level. Note that it would be intensively competitive and highly substitutive for these two channels if these values are large. That is, if the price of any one channel reduces by one unit, the demand in this a channel would increase $b_p + c_p$, which denotes the demand shift resulting from consumers who were originally unwilling to purchase, and customers who transfer their purchases from the other channel. Likewise, if the service level of any one channel increases one unit, the demand of this retailer would increase $b_s + c_s$. Therefore, the potential demand of the traditional retailer would thus be $\alpha a - b_pP_r + c_p(P_d - P_r) + b_sS_r - c_s(S_d - S_r)$; while the demand of the online retailer would be $(1-\alpha)a - b_pP_d + c_p(P_r - P_d) + b_sS_d - c_s(S_r - S_d)$ (Tsay and Agrawal, 2000). If there is no piracy in either channel, the potential demand is equal to the actual demand in each channel ($D_r' = D_r = \alpha a - b_pP_r + c_p(P_d - P_r) + b_sS_r - c_s(S_d - S_r)$; $D_d' = D_d = (1-\alpha)a - b_pP_d + c_p(P_r - P_d) + b_sS_d - c_s(S_r - S_d)$). However, these two demands are subject to vary due to piracy, and the decreased demand caused by this would be taken by both channels. It should be noted that an interaction exists between the two individual market channels. This means that the demand for any market channel will be influenced by both traditional and digital piracy, simultaneously. In other words, digital piracy does not only influence the digital market channel, but also the traditional one, and vice versa. For this reason, the potential demand of the traditional retailer with consideration of piracy is thus given by

$$D_r' = D_r + \alpha(\gamma_rD_r + \gamma_dD_d) = \alpha a - b_pP_r + c_p(P_d - P_r) + b_sS_r - c_s(S_d - S_r), \tag{1}$$

where $\gamma_rD_r + \gamma_dD_d$ denotes the amount of piracy for the entire market. With regard to the online retailer, the change in demand caused by piracy is the same as that of the traditional retailer, since both retailers face the same market, and the demand of the online retailer with consideration of piracy is thus given by

$$D_d' = D_d + (1-\alpha)(\gamma_rD_r + \gamma_dD_d) = (1-\alpha)a - b_pP_d + c_p(P_r - P_d) + b_sS_d - c_s(S_r - S_d). \tag{2}$$

Since the demands of the two channels interact because of piracy, the actual demands of the traditional retailer D_r and the online retailer D_d can be solved by simultaneous equations and algebraic operations. Accordingly, the actual demands of the traditional and digital channels can be given by

$$D_r = A_r - B_rP_r + C_rP_d, \tag{3}$$

and

$$D_d = A_d - B_dP_d + C_dP_r, \tag{4}$$

respectively, where

$$A_r = \frac{1+(1-\alpha)\gamma_d}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}\left(\left(\alpha - \frac{\alpha\gamma_d}{1+(1-\alpha)\gamma_d}(1-\alpha)\right)a + \left(b_s + c_s + \frac{\alpha\gamma_d}{1+(1-\alpha)\gamma_d}c_s\right)S_r - \left(c_s + \frac{\alpha\gamma_d}{1+(1-\alpha)\gamma_d}b_s + \frac{\alpha\gamma_d}{1+(1-\alpha)\gamma_d}c_s\right)S_d\right),$$

$$B_r = \frac{1+(1-\alpha)\gamma_d}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}\left(b_p + c_p + \frac{\alpha\gamma_d}{1+(1-\alpha)\gamma_d}c_p\right),$$

$$C_r = \frac{1+(1-\alpha)\gamma_d}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}\left(c_p + \frac{\alpha\gamma_d}{1+(1-\alpha)\gamma_d}b_p + \frac{\alpha\gamma_d}{1+(1-\alpha)\gamma_d}c_p\right),$$

$$A_d = \frac{1+\alpha\gamma_r}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}\left(\left(1-\alpha-\frac{(1-\alpha)\gamma_r}{1+\alpha\gamma_r}\alpha\right)a, + \left(b_s + c_s + \frac{(1-\alpha)\gamma_r}{1+\alpha\gamma_r}c_s\right)S_d - \left(c_s + \frac{(1-\alpha)\gamma_r}{1+\alpha\gamma_r}b_s + \frac{(1-\alpha)\gamma_r}{1+\alpha\gamma_r}c_s\right)S_r\right)$$

$$B_d = \frac{1+\alpha\gamma_r}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}\left(b_p + c_p + \frac{(1-\alpha)\gamma_r}{1+\alpha\gamma_r}c_p\right) \quad \text{and}$$

$$C_d = \frac{1+\alpha\gamma_r}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}\left(c_p + \frac{(1-\alpha)\gamma_r}{1+\alpha\gamma_r}b_p + \frac{(1-\alpha)\gamma_r}{1+\alpha\gamma_r}c_p\right).$$

Eqs. (3) and (4) indicate that, with consideration of piracy, the demand of any channel is in fact a function of its own and its competitor's retail prices. Hence, in the context of intense piracy, A_r and A_d can be interpreted as the market potential of the traditional and online retailers, respectively, B_r and B_d can be interpreted as the price elasticity on demand for the traditional and online retailers ($B_r = \partial D_r/\partial P_r$, $B_d = \partial D_d/\partial P_d$), and C_r and C_d can respectively be interpreted as the competitive intensity on price (i.e., cross-elasticity) of the traditional and online retailers ($C_r = \partial D_r/\partial P_d$, $C_d = \partial D_d/\partial P_r$). Note that the definitions of elasticity do not take the bases of demand and price into the consideration, and are slightly different from the general definition in economics. Moreover, if there is no piracy (i.e., $\gamma_r = \gamma_d = 0$), the demands in Eqs. (3) and (4) would degenerate to the demand for the ordinary products.

3.1. The profits of the supplier and retailers

In considering the wholesale price, the supplier negotiates with the traditional retailer to sell the product at price$(1-\theta^2)W_r$, and the retailer has to share θ ratio of the sales revenue with the supplier for every unit sold. As for the service cost, the traditional retailer has to invest more capital to provide better services to raise customer satisfaction. Here, it is assumed that the consumer value that is enhanced by the service provided by the traditional retailer would conform to the law of diminishing returns, i.e., the marginal profit gained would be less than the marginal cost born for providing a better level of service. Therefore, the service cost is presented as a quadratic convex function to reveal the concept of diminishing marginal service profit, which is given as $\eta_r \frac{{S_r}^2}{2}$ (Tsay & Agrawal, 2004), where η_r denotes the multiplier of the traditional retailer's service cost. The traditional retailer's total cost is thus given by

$$TC_r = \left(1-\theta^2\right)W_r D_r + \eta_r \frac{{S_r}^2}{2}. \tag{5}$$

The online retailer delivers products to consumers by online downloads or streams. The supplier negotiates with the online retailer that the product will be obtained by an initially fixed royalty charge, LF_d, and then a unit download fee of $(1-\theta^2)W_d$. Similarly, the revenue-sharing θwould be given to the supplier for every download in the future. Moreover, the online retailer also intends to provide better services by enhancing the quality of transmission, and the service cost also conforms to the law of diminishing returns, which is given as $\eta_d \frac{{S_d}^2}{2}$, where η_d denotes the multiplier of the online retailer's service cost. Since these two channels have different characteristics, the required cost would be different if a similar service level is desired, and the multipliers for these two channels would thus be different. The total cost of the online retailer is given by

$$TC_d = LF_d + \left(1-\theta^2\right)W_d D_d + \eta_d \frac{{S_d}^2}{2}. \tag{6}$$

With regard to the sales revenue, the traditional and online retailers have to share θ of revenue with the supplier when every unit is sold to consumers at prices P_r and P_d, respectively. Therefore, the sales revenue would be $(1-\theta)D_r P_r$, and the profit π_r for the traditional retailer is thus given by

$$\pi_r = (1-\theta)D_r P_r - TC_r. \tag{7}$$

On the other hand, the online retailer's sales revenue would be $(1-\theta)D_d P_d$, and the profit π_d is thus given by

$$\pi_d = (1-\theta)D_d P_d - TC_d. \tag{8}$$

The supplier initially sells different forms of products to the two different retailers with different wholesale prices, and obtains a share of sales revenue from the two retailers for every product they sell. Therefore, the supplier's revenue would be $\theta(D_r P_r + D_d P_d) + (1-\theta^2)$-$D_r P_r + D_d P_d) + (1-\theta^2) D_r W_r + (1-\theta^2) D_d W_d + LF_d$. *Considering the cost of purchasing the copyright from the product creator, LF_s, and the channel costs for both channels, i.e., W_r and W_d, the supplier's profit is thus given by*

$$\pi_s = \theta(D_r P_r + D_d P_d) - \theta^2 (D_r W_r + D_d W_d) + LF_d - LF_s. \tag{9}$$

Note that the parameters α, a, b_p, c_p, b_s, c_s, γ_r, γ_d, η_r, and η_d can be obtained by marketing surveys and statistical analyses conducted by the marketing department.

Since the supplier acts as a leader in the Stackelberg game, while the two retailers act as followers, a backward derivation process can be used to obtain the response retail prices.

Lemma 1. *The response retail prices of the two retailers if the supplier's revenue-sharing ratio is θ are given by*

$$P_r(\theta) = \frac{2A_r B_d + A_d C_r}{4B_d B_r - C_d C_r} + (1+\theta)\frac{B_d(2B_r W_r + C_r W_d)}{4B_d B_r - C_d C_r}, \tag{10}$$

and

$$P_d(\theta) = \frac{2A_d B_r + A_r C_d}{4B_d B_r - C_d C_r} + (1+\theta)\frac{B_r(2B_d W_d + C_d W_r)}{4B_d B_r - C_d C_r}, \tag{11}$$

respectively.

Proof: Please see Appendix A.

Since $B_r > C_r$ and $B_d > C_d$ are obvious by simple algebraic operations, we can thus have $\frac{B_d(2B_r W_r + C_r W_d)}{4B_d B_r - C_d C_r} > 0$ and $\frac{B_r(2B_d W_d + C_d W_r)}{4B_d B_r - C_d C_r} > 0$, which indicate that, in Lemma 2, the retail prices are linearly and positively correlated to the revenue-sharing ratio, i.e., the retail prices would increase along with the revenue-sharing ratio set by the supplier. This is a useful mechanism to prevent a price war among retailers for industries which have extremely low marginal cost, such as the digital goods industry. Once the supplier recognizes that some retailers offer an unreasonably low price to drive up demand, the supplier can raise the revenue-sharing ratio to force these retailers to set their prices back to a reasonable level. By substituting the two response retail prices obtained from Lemma 2 into the supplier's profit, the profit can thus be rearranged as

$$\pi_s = \Phi\theta^3 + \Psi\theta^2 + \Omega\theta + LF_d - LF_s, \tag{12}$$

where

$$\Phi = \frac{B_d(2B_d B_r W_d - C_d C_r W_d - B_r C_d W_r)^2}{(4B_d B_r - C_d C_r)^2} + \frac{B_r(2B_d B_r W_r - C_d C_r W_r - B_d C_r W_d)^2}{(4B_d B_r - C_d C_r)^2},$$

$$\Psi = -\frac{B_d(2B_dB_rW_d - C_dC_rW_d - B_rC_dW_r)(4A_dB_r + 2A_rC_d + C_dC_rW_d + 2B_rC_dW_r)}{(4B_dB_r - C_dC_r)^2} - \frac{B_r(2B_dB_rW_r - C_dC_rW_r - B_dC_rW_d)(4A_rB_d + 2A_dC_r + 2B_dC_rW_d + C_dC_rW_r)}{(4B_dB_r - C_dC_r)^2},$$

and

$$\Omega = \frac{B_d(2A_dB_r + A_rC_d + 2B_dB_rW_d + B_rC_dW_r)(2A_dB_r + A_rC_d - 2B_dB_rW_d + C_dC_rW_d + B_rC_dW_r)}{(4B_dB_r - C_dC_r)^2} + \frac{B_r(2A_rB_d + A_dC_r + B_dC_rW_d + 2B_dB_rW_r)(2A_rB_d + A_dC_r - 2B_dB_rW_r + C_dC_rW_r + B_dC_rW_d)}{(4B_dB_r - C_dC_r)^2}.$$

3.2. The equilibrium strategies of the supplier and retailers

Since $B_r > C_r$ and $W_r \geq W_d$, we have $2B_dB_rW_r - C_dC_rW_r - B_dC_rW_d > 0$ and thus $\Phi > 0$. Accordingly, the supplier's profit is a cubic function with a positive coefficient on the third-order term. Upon learning the retailers' possible strategies, the supplier can thus obtain the optimal revenue-sharing ratio.

Lemma 2. *With consideration of piracy, if the price elasticity of the traditional channel is within a range as* $\frac{1}{2}\frac{A_r}{W_r} + \frac{C_rW_d}{W_r} \leq B_r \leq \frac{2}{3}\frac{A_r}{W_r} + \frac{C_rW_d}{W_r}$, *and the price elasticity of the digital channel is within a range as* $\frac{1}{2}\frac{A_d}{W_d} + \frac{C_dW_r}{W_d} \leq B_d \leq \frac{2}{3}\frac{A_d}{W_d} + \frac{C_dW_r}{W_d}$; *or if the two channels set their prices as their corresponding channel costs and their demands are within 1/3 to 1/2 of their corresponding market potentials, then* $\theta^* = \frac{-\Psi - \sqrt{\Psi^2 - 3\Phi\Omega}}{3\Phi}$ *would be the supplier's optimal revenue-sharing ratio.*

Proof: Please see Appendix A.

According to the previous three Lemmas, with consideration of piracy, there exists an optimal revenue-sharing ratio if both channels have specific levels of price elasticity. In addition, the supplier would take advantage of the adjustment of the revenue-sharing ratio to prevent the two retailers from setting their retail prices too high or too low.

Theorem 1. *With consideration of piracy, the supplier has an optimal Nash equilibrium revenue-sharing ratio which is given by*

$$\theta^* = \frac{-\Psi - \sqrt{\Psi^2 - 3\Phi\Omega}}{3\Phi}, \tag{13}$$

while the optimal Nash equilibrium retail prices for the traditional and online retailers are

$$P_r^* = \frac{2A_rB_d + A_dC_r}{4B_dB_r - C_dC_r} + (1+\theta^*)\frac{b_d(C_rW_d + 2B_rW_r)}{4B_dB_r - C_dC_r}, \tag{14}$$

and

$$P_d^* = \frac{2A_dB_r + A_rC_d}{4B_dB_r - C_dC_r} + (1+\theta^*)\frac{B_r(2B_dW_d + C_dW_r)}{4B_dB_r - C_dC_r}, \tag{15}$$

respectively.

Proof: Please see Appendix A.

Theorem 1 gives the equilibrium prices of P_r^* and P_d^* which are derived after considering the equilibrium revenue-sharing ratio, and this ratio is determined by the supplier upon learning the two retailers' possible retail prices.

4. Analytical and numerical investigation

Since market demand would be affected by piracy, market potential, price elasticity, and cross price elasticity, it is essential for managers to respond to the change in demand due to these factors and achieve a win-win case of supply chain coordination.

4.1. Analysis of properties

Since piracy of digital goods is common, the demands of the retailers would not be as high as originally estimated, and thus some adjustments are required to better depict the actual demand.

Proposition 1. *With consideration of piracy, the demand of*

(1) *the traditional channel is linearly correlated to its original demand without piracy. It is adjusted by multiplying a factor of* $\frac{1+(1-\alpha)\gamma_d}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}$ *for its original demand, and then subtracting the original demand of the digital channel with a factor of* $\frac{\alpha\gamma_d}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}$.
(2) *the digital channel is linearly correlated to its original demand without piracy. It is adjusted by multiplying a factor of* $\frac{1+\alpha\gamma_r}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}$ *for its original demand, and then subtracting the original demand of the traditional channel with a factor of* $\frac{(1-\alpha)\gamma_r}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}$.

Proof: Please see Appendix A.

According to Proposition 1, there is a linear relationship for the demands with and without piracy. The changes in demands for the traditional and digital channels are with the factors of $\frac{1+(1-\alpha)\gamma_d}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}$ and $\frac{1+\alpha\gamma_r}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}$, respectively. Since piracy does alter the market demand, the entire market potential also changes.

Proposition 2. *The demands of both channels decrease as piracy occurs in the market, and the total market potential would remain only* $\frac{a}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}$ *which is smaller as piracy is more prevalent.*

Proof: Please see Appendix A.

Proposition 2 reveals that the demands of both channels decrease owing to piracy, and the total market potential would decrease as piracy becomes more serious. Therefore, the two retailers would compete with each other in a smaller market due to piracy.

Proposition 3. *With consideration of piracy,*

(1) *the price elasticity of the traditional retailer,* B_r, *compared with that without piracy, would be less if* $\frac{\gamma_r}{\gamma_d} > \frac{c_p}{b_p+c_p}$, *the same if* $\frac{\gamma_r}{\gamma_d} = \frac{c_p}{b_p+c_p}$, *and greater if* $\frac{\gamma_r}{\gamma_d} < \frac{c_p}{b_p+c_p}$. *Similarly, the price elasticity of the online retailer,* B_d, *compared with that without piracy, would be less if* $\frac{\gamma_r}{\gamma_d} < \frac{b_p+c_p}{c_p}$, *the same if* $\frac{\gamma_r}{\gamma_d} = \frac{b_p+c_p}{c_p}$, *and greater if* $\frac{\gamma_r}{\gamma_d} > \frac{b_p+c_p}{c_p}$.
(2) *The price elasticity of any channel would be lower when its piracy rate is higher, but higher when its competitor's piracy rate is higher.*

Proof: Please see Appendix A.

According to Proposition 3, the price elasticity would decrease due to the increase in the piracy rate of the channel itself, and increase due to the rise in the piracy rate of the competitor channel. The price is less sensitive for a channel with high a piracy rate, and thus the channel retailer would not be able to gain more demand by decreasing the selling price. However, if its competitor has a high piracy ratio, the price elasticity would increase, and more consumers would be attracted by decreasing the selling price. Therefore, the retailer with a low piracy rate can enhance its profit by attracting more consumers to purchase the product by lowering its selling price. This is an important incentive for a retailer to take effective activities to achieve a low piracy rate.

Proposition 4. *Piracy may influence the relationship between price elasticity and the market share.*

(1) *When* $\gamma_r = \gamma_d = 0$, *the price elasticity would remain the same as the market share increases.*
(2) *When the piracy rates of the two retailers are not zero, the price elasticity would change as the market share changes.*

Proof: Please see Appendix A.

Proposition 4 reveals that the price elasticity of the channel would vary as the market share changes. If a channel pursues a low piracy rate and a high market share, its price elasticity would increase, and such a channel would thus be able to attract more consumers to purchase its products and enhance its profit by lowering the selling price.

Proposition 5. *With consideration of piracy*,

(1) *the competitive intensity of the traditional retailer (i.e., cross elasticity), compared with that without piracy, would be mild if* $\frac{\gamma_r}{\gamma_d} > \frac{c_p+b_p}{c_p}$, *and be severe if* $\frac{\gamma_r}{\gamma_d} < \frac{c_p+b_p}{c_p}$; *while the competitive intensity of the online retailer, compared with that without piracy, would be severe if* $\frac{\gamma_d}{\gamma_r} < \frac{c_p+b_p}{c_p}$, *and be mild if* $\frac{\gamma_d}{\gamma_r} > \frac{c_p+b_p}{c_p}$.

(2) *The cross elasticity would be smaller when the channel's piracy rate is higher, while the cross elasticity would be larger if the competitor's piracy rate is higher, and the competition would also be more intense.*

Proof: Please see Appendix A.

Proposition 5 reveals that the competitive intensity (i.e., cross elasticity) would change due to piracy, and the price competition of the two channels would be more intensive as the competitive intensity increases. Moreover, the channel's cross elasticity would increase as its piracy rate decreases, which indicates that the demand would increase as the competitor increases its retail price. In addition, the aforementioned discussion with consideration of piracy shows that the channel with a low piracy rate would have more opportunities to increase its profit. Therefore, the retailer would thus have incentives to undertake effective activities to achieve a lower piracy rate.

Proposition 6. *If* $b_p > c_p$, *which are the price elasticity and cross elasticity of the original market without piracy, respectively, and the two channels have the same service level and piracy rate, then the retailer with a higher market share can set a higher retail price under Nash equilibrium.*

Proof: Please see Appendix A.

It was demonstrated previously that the retailer can obtain more profits if it has a lower piracy rate. However, according to Proposition 6, the channel with a higher market share can set a relatively high retail price to obtain more profit when the two channels have the same piracy rate. Therefore, the retailer should aim to increase its market share to obtain more profit.

Proposition 7. *If the two channels have the same service level and wholesale price, then the retailer with a higher market share can set a higher retail price when its competitor has a higher piracy rate under Nash equilibrium.*

Proof: Please see Appendix A.

Proposition 7 reveals that the retailer with a higher market share should have a higher retail price if its competitor has a higher piracy rate. If the two retailers have the same cost, the channel with a higher market share and a higher retail price would thus obtain more profit. Therefore, the retailer should endeavor to pursue a high market share and a low piracy rate.

Proposition 8. *If there is no piracy in the market, and the two channels have the same market share and service level, then the retail price would increase as the wholesale price increases under Nash equilibrium.*

Proof: Please see Appendix A.

Proposition 8 reveals that there is a positive correlation between the wholesale price and retail price in an equilibrium status, when there is no piracy in the market and the two channels have the same market share and service level.

4.2. Numerical applications

Suppose that a film supplier purchases the copyright of a movie from its director in Taiwan, and the royalty fee (fixed cost) is \$2600. The supplier sells the movie by both traditional and online retailers in the forms of physical DVDs and an online stream, and would pay the royalty charge to the movie director for each sold unit. Suppose that the traditional retailer sell the physical DVDs, and it needs to pay \$8 per unit to the supplier for the royalty charge and the production cost (including art design, packaging and physical DVD). However, the online retailers only pay \$4 for the royalty charge. The mutually agreeable coordination mechanism is that the supplier has to sell a unit to the two retailers at a price which is lower than its unit cost, and the two retailers share their sales revenues with the supplier for every unit is sold. The wholesale price would thus be lower as the shared revenue increases. Moreover, in addition to the unit cost, the online retailer should pay for authorization from the supplier to be able to provide consumers with download privileges, which costs \$1800.

It is assumed that the total market potential of the movie is 6000 units, and the market shares of the traditional and the online retailers are 0.6 and 0.4, respectively. Since the demand would vary with price and service level, the price elasticity on demand is 55, the price competitive intensity is 5, the service elasticity on demand is 12, and the service competitive intensity is 9, according to a survey conducted by the marketing department. The service levels for the traditional and the digital channels are 0.8 and 0.7, respectively. Since piracy occurs in the market, it is estimated that the piracy rate of the traditional channel would be 0.1, while that of the digital channel would be 0.25. Owing to the different characteristics of the two channels, the costs of offering similar service levels would be different, and the multipliers of the service level for the traditional and online retailers are assumed to be 3 and 2, respectively. Upon obtaining this information, the optimal equilibrium prices for the supplier and the two retailers can be obtained by using the approach proposed in this study, and the optimal revenue-sharing ratio can also be determined. Table 2 shows the parameter settings for the supplier and two retailers.

In considering the impacts of piracy on the market potential, price elasticity, and cross-elasticity on demand, their values differ from those of the original case without piracy, and the results are shown in Table 3.

As can be seen from Table 3, owing to piracy, the market potential would decrease, the price elasticity would decrease, and the competitive intensity (i.e., cross-elasticity) would increase. Moreover, Table 4 shows a comparison of pricing strategies under Nash equilibrium between the supplier and the two retailers with and without piracy.

As can be seen in Table 4, when piracy occurs in the market, since the market potential decreases, the supplier would urge the two retailers to reduce their retail prices by decreasing the revenue-sharing ratio to gain more demand and thus achieve profits for all the members of the supply chain. However, the resulting profit, compared to the market without piracy, would be lower due to the decreased demand and retail prices.

In order to further understand how the changes in the piracy rate affect the profits of the channel members, sensitivity analyses are performed by changing this rate within a specific range and investigating

Table 2
The parameter settings.

Parameters	Values	Parameters	Values
a	6000	η_r	3
α	0.6	γ_d	0.25
b_p	55	S_d	0.7
c_p	5	η_d	2
γ_r	0.1	W_r	8
b_s	12	W_d	4
c_s	9	LF_s	2600
S_r	0.8	LF_d	1800

Table 3
The relative parameters with and without piracy.

Channel members	Parameters	Without piracy	With piracy
Traditional retailer	A_r	2975.87	2835.67
	B_r	60.62	57.76
	C_r	12.42	11.83
Online retailer	A_d	2433.71	2319.01
	B_d	53.93	54.411
	C_d	8.99	10.67

the derivations of the profit for the channel members. Fig. 2 shows the results when the piracy rate of the traditional channel varies. Note that the maximum of the change in the piracy rate is set to be 0.7 in this study, since the piracy rate is often not that high in real world situations. Moreover, Fig. 3 shows the results of the sensitivity analysis when considering the effects of the changes in the digital channel's piracy rate.

As can be seen in Fig. 2, the profit of every member in the supply chain would decrease due to the increase in the piracy rate of the traditional channel, and the digital channel's profit is most affected. This can be explained by the fact that since the online retailer has to pay a fixed royalty charge before selling the product, it needs to manipulate the sales volume to offset the large fixed cost. If the sales volume is small, the fixed cost would not be offset, which results in a low profit and high sensitivity situation. Moreover, if the royalty charge is low, the digital channel's profit is less sensitive to the traditional channel's piracy rate than the other two channel members'. Note that the supplier, compared to the two retailers, has more profit gains and less profit changes. As can be seen in Fig. 3, the profit of every member in the supply chain would decrease as the piracy rate of the digital channel increases, and the digital channel is the most sensitive to this, while the supplier is the least. Based on Figs. 2 and 3, the profits for all members in the supply chain would decrease as the piracy rate of either channel increases. In addition, the traditional channel is more affected by its own piracy rate than by that of the digital channel. Accordingly, the traditional retailer should pay more attention to its own piracy rate in the market, since a high rate would severely affect its own profit. Note that the differences are not significant for the changes in profit of the supplier, the online retailer, and the entire supply chain, no matter whether piracy occurs in the traditional or digital channel.

Based on the above discussion, some important managerial insights and suggestions for the supplier and retailers are as follows: (1) In order to avoid a price war among retailers, the supplier can raise the revenue-sharing ratio to force these retailers to set their prices back to a reasonable level if the supplier recognizes that some retailers offer an unreasonably low price to drive up demand. (2) If the demands of both channels decrease due to piracy, the two retailers would be forced to compete with each other in a smaller market. (3) If a retailer's competitor has a high piracy rate, the price elasticity would increase, and more consumers would be attracted by decreasing the selling price. Therefore, the retailer with a low piracy rate can enhance its profit by lowering its selling price. (4) The price elasticity of the channel would vary as the market share changes. If a channel pursues a low piracy rate and a high market share, its price elasticity would increase. (5) The competitive intensity will change due to piracy, and the price competition of the two channels would be more intensive as the competitive intensity increases. Therefore, the retailer should have incentives to undertake effective activities to achieve a lower piracy rate.

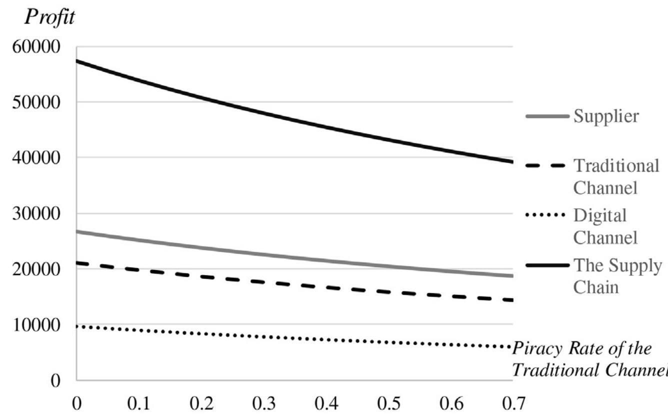

Fig. 2. The Profit as the piracy rate of the traditional channel changes.

5. Conclusion

This study considers the coordination of revenue-sharing between the supplier and two retailers for digital goods. A Stackelberg game is utilized to obtain the optimal revenue-sharing ratio which is determined by the supplier and is used by all channel members. In considering the competition of service and price and the impact of piracy, the two retailers can obtain the equilibrium retail prices according to their own cost structures and their conjectures about the other's possible strategies. For all channel members, with the equilibrium retail prices and the mechanism of revenue sharing, the profit of the supply chain as a whole would be maximized, and thus a win-win situation is achieved. Moreover, for those industries with an extremely low marginal cost that are often afraid of experiencing price wars, the adoption of revenue-sharing coordination and equilibrium prices gives retailers incentives to determine reasonable retail prices, and thus prevent the double marginalization that can arise from individual channel members maximizing their own profits, so avoiding a price war. This may greatly benefit industries with extremely low marginal costs, such as those providing digital goods which are sold by many channels.

In order to prevent decreases in demand, both suppliers and retailers should devote themselves to preventing piracy. Moreover, the demand would also be affected if the pirated product can be copied again, and thus the re-piracy rate can be considered in future studies. In addition, if the two channels are substantially heterogeneous, the supplier may have different mechanisms of coordination with respect to different

Table 4
Comparison of pricing strategies with and without piracy.

Channel members	Price and profit	Without piracy	With piracy
Traditional retailer	Retail price	35.57	32.66
	Profit	24,609	19,799
Online retailer	Retail price	22.80	21.66
	Profit	11,459	9033
Supplier	Revenue-Sharing Ratio	0.371	0.389
	Profit	28,062	25,096
The profit of the supply chain		64,130	53,928

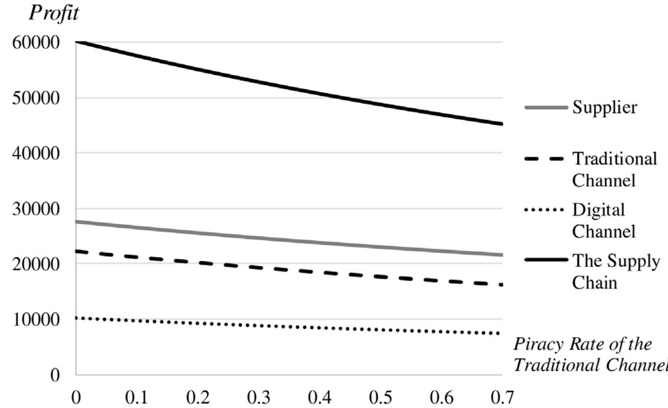

Fig. 3. The profit as the piracy rate of the digital channel changes.

retailers, such as different revenue-sharing ratios. Since this study focuses only on the Stackelberg game in which the supplier is a leader and the two retailers are followers, the problem of multiple suppliers and three or more retailers in the market with different competitive games may be considered in the future. In addition, future studies may be extended by considering the royalty charge for transferring the copyright as another decision variable which can be determined by the supplier, since a more innovative intellectual property may be more highly valued. Finally, the issues of shortage, inventory, and scrap value may also be included in future studies.

Appendix A

A.1. Proof of Lemma 1

Since $\frac{\partial^2 \pi_r}{\partial {P_r}^2} = -2(1-\theta)B_r < 0$ and $\frac{\partial^2 \pi_d}{\partial {P_d}^2} = -2(1-\theta)B_d < 0$, there exist the optimal prices for these two retailers to maximize their profits. The two retailers' response retail prices can thus be obtained by letting the first-order derivative for Eqs. (7) and (8) with respect to P_r and P_d be zero and solving the simultaneous equations.

A.2. Proof of Lemma 2

By taking the first-order derivative with respect to θ from Eq. (12), we can have $\frac{\partial \pi_s}{\partial \theta} = 3\Phi\theta^2 + 2\Psi\theta + \Omega$

(1) *The existence of the optimal solution*
The existence of the maximal profit requires $\frac{\partial^2 \pi_s}{\partial \theta^2} = 6\Phi\theta + 2\Psi < 0$. Since we have $0 \le \theta \le 1$ and $\Phi > 0$, θ would be optimal within the close interval [0,1] if $3\Phi + \Psi < 0$ is satisfied. Moreover, since $2B_dB_rW_r - C_dC_rW_r - B_dC_rW_d > 0$, if we can have

$$2B_dB_rW_d - C_dC_rW_d - B_rC_dW_r > 0, \tag{A1}$$

then $3\Phi + \Psi < 0$ would hold once the two inequalities $3(2B_dB_rW_d - C_dC_rW_d - B_rC_dW_r) < 4A_dB_r + 2A_rC_d + C_dC_rW_d + 2B_rC_dW_r$ and $3(2B_dB_rW_r - C_dC_rW_r - B_dC_rW_d) < 4A_rB_d + 2A_dC_r + 2B_dC_rW_d + C_dC_rW_r$ are also true. The above two inequalities can be rearranged as
$3B_dB_rW_d - 2C_dC_rW_d - \frac{5}{2}B_rC_dW_r < 2A_dB_r + A_rC_d$ and $3B_d B_rW_r - 2C_d C_rW_r - \frac{5}{2}B_dC_rW_d < 2A_rB_d + A_dC_r$. Since $3B_dB_rW_d - 2C_dC_rW_d - \frac{5}{2}B_rC_dW_r < 3B_dB_rW_d - \frac{3}{2}C_dC_rW_d - \frac{3}{2}B_rC_dW_r$ and $3B_dB_rW_r - 2C_dC_rW_r - \frac{5}{2}B_dC_rW_d < 3B_dB_rW_r - \frac{3}{2}C_dC_rW_r - \frac{3}{2}B_dC_rW_d$, we then have

$$3B_dB_rW_d - \frac{3}{2}C_dC_rW_d - \frac{3}{2}B_rC_dW_r \le 2A_dB_r + A_rC_d, \tag{A2}$$

and

$$3B_dB_rW_r - \frac{3}{2}C_dC_rW_r - \frac{3}{2}B_dC_rW_d \le 2A_rB_d + A_dC_r. \tag{A3}$$

Therefore, Eqs. (A1), (A2), and (A3) are the necessary conditions for the existence of the optimal solution. Moreover, $\Psi < 0$can be derived from Eq. (A1), and $\Omega \ge 0$ can be derived from Eqs. (A2) and (A3).

(2) *Searching for the optimal solution*
The maximum profit may occur at either the two extreme ends or the inflection points. The inflection points can be obtained by letting equation $\frac{\partial \pi_s}{\partial \theta}$ be zero, and these are given by $\theta = \frac{-\Psi \pm \sqrt{\Psi^2 - 3\Phi\Omega}}{3\Phi}$ if $\Psi^2 - 3\Phi\Omega \ge 0$. Since $\Phi > 0$, the local maximum is thus located at $\theta_{l\max} = \frac{-\Psi - \sqrt{\Psi^2 - 3\Phi\Omega}}{3\Phi}$; while $\theta_{l\min} = \frac{-\Psi + \sqrt{\Psi^2 - 3\Phi\Omega}}{3\Phi}$would be the local minimum. When $3\Phi + \Psi < 0$ and $\Omega \ge 0$, the two real solutions would be $\theta_{l\max} > 0$ and $1 < \theta_{l\min}$. Moreover, if $-\Psi \ge \Omega$, the local maximum would be located within the closed interval between 0 and 1, i.e., $0 \le \theta_{l\max} \le 1$. Fig. 1 shows the supplier's profit function and the optimal solutions.

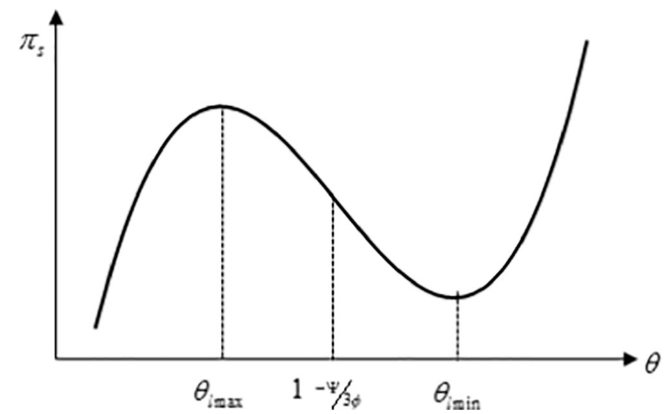

Fig. 1. The supplier's profit function.

Based on the aforementioned discussion, if the two inequalities

$$2B_dB_rW_d - B_rC_dW_r - C_dC_rW_d \le 2A_dB_r + A_rC_d \le 2(2B_dB_rW_d - B_rC_dW_r - C_dC_rW_d), \tag{A4}$$

and

$$2B_dB_rW_d - B_rC_dW_r - C_dC_rW_d \le 2A_rB_d + A_dC_r \le 2(2B_dB_rW_r - B_dC_rW_d - C_dC_rW_r) \tag{A5}$$

are satisfied, we then have $-\Psi \ge \Omega \ge 0$. However, the maximum value may also occur at the two extreme ends. It is thus necessary to examine whether the profits at the two extreme ends are less than that of the local maximum, i.e., $\pi_s(\theta_{l\max}) \ge \pi_s(1)$ and $\pi_s(\theta_{l\max}) \ge \pi_s(0)$, which is obviously true when $3\Phi + \Psi < 0$ and $-\Psi \ge \Omega \ge 0$. Therefore, the optimal solution is thus confirmed as $\theta^* = \theta_{l\max}$. By integrating and rearranging Eqs. (A1) to (A5), we have.

$$\frac{3}{2}(2B_dB_rW_r - C_dC_rW_r - B_dC_rW_d) \le 2A_rB_d + A_dC_r \le 2(2B_dB_rW_r - C_dC_rW_r - B_dC_rW_d), \tag{A6}$$

and

$$\frac{3}{2}(2B_dB_rW_d - C_dC_rW_d - B_rC_dW_r) \le 2A_dB_r + A_rC_d \le 2(2B_dB_rW_d - C_dC_rW_d - B_rC_dW_r). \tag{A7}$$

This indicates that once Eqs. (A6) and (A7) are satisfied, there exists an optimal solution of the revenue-sharing ratio which is within the range of [0, 1]. Accordingly, as the price elasticities are given as $\frac{1}{2}\frac{A_r}{W_r} + \frac{C_rW_d}{W_r} \le B_r \le \frac{2}{3}\frac{A_r}{W_r} + \frac{C_rW_d}{W_r}$, and $\frac{1}{2}\frac{A_d}{W_d} + \frac{C_dW_r}{W_d} \le B_d \le \frac{2}{3}\frac{A_d}{W_d} + \frac{C_dW_r}{W_d}$, for the traditional and digital channels, respectively, Eqs. (A6) and (A7) can be satisfied, and the supplier's optimal revenue-sharing ratio would be $\theta^* = \frac{-\Psi - \sqrt{\Psi^2 - 3\Phi\Omega}}{3\Phi}$. Moreover, these two inequalities can be rearranged as $\frac{1}{3}A_r \le A_r - B_rW_r + C_rW_d \le \frac{1}{2}A_r$ and $\frac{1}{3}A_d \le A_d - B_dW_d + C_dW_r \le \frac{1}{2}A_d$, which imply that if the two channels set their prices as their corresponding channels costs, their demand would be within 1/3 and 1/2 of their corresponding market potentials.

A.3. Proof of Theorem 1

Based on Lemmas 1, 2, and 3, the two retailers' optimal retail prices can be obtained by substituting the supplier's optimal revenue-sharing ratio into the two retailers' optimal response retail prices.

A.4. Proof of Proposition 1

(1) *Since the original demands of the traditional and digital channels without piracy are* $\alpha a-(b_p+c_p)P_r+c_pP_d+(b_s+c_s)S_r-c_sS_d$ *and* $(1-\alpha)a-(b_p+c_p)P_d+c_pP_r+(b_s+c_s)S_d-c_sS_r$*, respectively, equation (3) in Lemma 1 can be rearranged as.*

$$D_r=\frac{1+(1-\alpha)\gamma_d}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}(\alpha a-(b_p+c_p)P_r+c_pP_d+(b_s+c_s)S_r-c_sS_d)\\-\frac{\alpha\gamma_d}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}((1-\alpha)a-(b_p+c_p)P_d+c_pP_r+(b_s+c_s)S_d-c_sS_r).$$

Therefore, the demands of the traditional channel with and without piracy are linearly correlated, and the adjustment due to piracy is demonstrated.

(2) *Since Eq. (4) in Lemma 1 can be rearranged as.*

$$D_d=\frac{1+\alpha\gamma_r}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}((1-\alpha)a-(b_p+c_p)P_d+c_pP_r+(b_s+c_s)S_d-c_sS_r)\\-\frac{(1-\alpha)\gamma_r}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}(\alpha a-(b_p+c_p)P_r+c_pP_d+(b_s+c_s)S_r-c_sS_d),$$

the demands of the digital channel with and without piracy are thus linearly correlated, and the adjustment due to piracy is demonstrated.

A.5. Proof of Proposition 2

As the retail prices and service levels of the two retailers are zero, the difference in demand for the traditional channel with and without piracy is given by $\alpha a-\frac{1+(1-\alpha)\gamma_d}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}(\alpha-\frac{\alpha\gamma_d}{1+(1-\alpha)\gamma_d}(1-\alpha))a=\frac{\alpha(\gamma_r-\gamma_d)+\gamma_d}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}\alpha a>0$*, i.e.,* $\alpha a>A_r$*. Therefore, the demand of the traditional channel would decrease owing to piracy. Likewise, the difference in demand of the digital channel is given by* $(1-\alpha)a-\frac{1+\alpha\gamma_r}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}((1-\alpha)-\frac{(1-\alpha)\gamma_r}{1+\alpha r_r}\alpha)a=\frac{\alpha(\gamma_r-\gamma_d)+\gamma_d}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}(1-\alpha)a>0$*, i.e.,* $(1-\alpha)a>A_d$*. Therefore, the demand of the digital channel would also decrease owing to piracy. Accordingly, with consideration of piracy, the total market potential is given by* $A_r+A_d=\frac{a}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}$*, which reveals that the market potential would decrease from a to* $\frac{a}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}$ *due to piracy, and the decrease would be more severe as* γ_r *and* γ_d *increase.*

A.6. Proof of Proposition 3

(1) *For the traditional retailer, the difference in the price elasticity without and with piracy is given by* $(b_p+c_p)-B_r=\frac{\alpha((b_p+c_p)\gamma_r-c_p\gamma_d)}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}$*. It can thus be observed that* $b_p+c_p>B_r$ *when* $\frac{\gamma_r}{\gamma_d}>\frac{c_p}{b_p+c_p}$*, while* $b_p+c_p=B_r$ *when* $\frac{\gamma_r}{\gamma_d}=\frac{c_p}{b_p+c_p}$*; and* $b_p+c_p<B_r$ *when* $\frac{\gamma_r}{\gamma_d}<\frac{c_p}{b_p+c_p}$*. Likewise, for the digital channel, the difference in the price elasticity without and with piracy is given by* $(b_p+c_p)-B_d=\frac{(1-\alpha)((b_p+c_p)\gamma_d-c_p\gamma_r)}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}$*. It can thus be observed that* $b_p+c_p>B_d$ *when* $\frac{\gamma_r}{\gamma_d}<\frac{b_p+c_p}{c_p}$*, while* $b_p+c_p=B_d$ *when* $\frac{\gamma_r}{\gamma_d}=\frac{b_p+c_p}{c_p}$*, and* $b_p+c_p<B_d$ *when* $\frac{\gamma_r}{\gamma_d}>\frac{b_p+c_p}{c_p}$*.*

(2) *Since we have* $\frac{\partial B_r}{\partial\gamma_r}=\frac{-\alpha(c_p(1+\gamma_d)+b_p(1+(1-\alpha)\gamma_d)}{(1+\alpha\gamma_r+(1-\alpha)\gamma_d)^2}<0$ *and* $\frac{\partial B_d}{\partial\gamma_d}=\frac{-(1-\alpha)(c_p(1+\gamma_r)+b_p(1+\alpha\gamma_r))}{(1+\alpha\gamma_r+(1-\alpha)\gamma_d)^2}<0$*, this indicates that the price elasticity of a channel would decrease as its piracy rate increases. Conversely, we have* $\frac{\partial B_r}{\partial\gamma_d}=\frac{\alpha((1-\alpha)\gamma_rb_p+c_p(1+\gamma_r))}{(1+\alpha\gamma_r+(1-\alpha)\gamma_d)^2}>0$ *and* $\frac{\partial B_d}{\partial\gamma_r}=\frac{(1-\alpha)(\alpha\gamma_db_p+c_p(1+\gamma_d))}{(1+\alpha\gamma_r+(1-\alpha)\gamma_d)^2}>0$*, which indicates that the price elasticity of the channel would increase as the piracy rate of its competitor channel increases.*

A.7. Proof of Proposition 4

(1) *When* $\gamma_r=\gamma_d=0$*, we have* $B_r=B_d=b_p+c_p$ *which indicates that price elasticity is irrelevant to the market shares of the two retailers.*

(2) *By taking the first-order derivative for the price elasticity of the traditional channel with respect to its own market share, we have* $\frac{\partial B_r}{\partial\alpha}=\frac{-(1+\gamma_d)(b_p\gamma_r+c_p(\gamma_r-\gamma_d))}{(1+\alpha\gamma_r+(1-\alpha)\gamma_d)^2}$*. It can thus be seen that when* $\gamma_r>\gamma_d$*,* B_r *would decrease as* α *increases. In addition,* B_r *would increase as* α *increases when* $c_p\gamma_d>(b_p+c_p)\gamma_r$*, while* B_r *would remain the same as* α *changes when* $c_p\gamma_d=(b_p+c_p)\gamma_r$*. Likewise, since we have* $\frac{\partial B_d}{\partial(1-\alpha)}=\frac{-(1+\gamma_r)(b_p\gamma_d+c_p(\gamma_d-\gamma_r))}{(1+\alpha\gamma_r+(1-\alpha)\gamma_d)^2}$*, it can be seen that when* $\gamma_r<\gamma_d$*,* B_d *would decrease as* $(1-\alpha)$ *increases. Moreover,* B_d *would decrease as* $1-\alpha$ *increases when* $c_p\gamma_r>(b_p+c_p)\gamma_d$*, while* B_d *would remain the same as* $(1-\alpha)$ *changes when* $c_p\gamma_d=(b_p+c_p)\gamma_r$*.*

A.8. Proof of Proposition 5

(1) *With consideration of piracy, the difference in the cross-price elasticity of the traditional retailer, compared to that without piracy, is given as* $c_p-C_r=\frac{\alpha(\gamma_r-\gamma_d)}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}c_p-\frac{\alpha\gamma_d}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}b_p$*. If* $\frac{\gamma_r}{\gamma_d}>\frac{c_p+b_p}{c_p}$*, then* $c_p-C_r>0$ *which indicates that the competition would be milder when piracy is in such a condition; while if* $\frac{\gamma_r}{\gamma_d}<\frac{c_p+b_p}{c_p}$*, then* $c_p-C_r<0$*, which indicates that the competition would be more intensive. Likewise, the difference in the cross-price elasticity of the online retailer, compared to that without piracy, is given as* $c_p-C_d=\frac{(1-\alpha)(\gamma_d-\gamma_r)}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}c_p-\frac{(1-\alpha)\gamma_r}{1+\alpha\gamma_r+(1-\alpha)\gamma_d}b_p$*. If* $\frac{\gamma_d}{\gamma_r}>\frac{c_p+b_p}{c_p}$*, then* $c_p-C_d>0$*, which indicates that the competition would be milder when piracy is in such a condition; while if* $\frac{\gamma_d}{\gamma_r}<\frac{c_p+b_p}{c_p}$*, then* $c_p-C_d<0$ *which indicates that the competition would be more intensive.*

(2) *Since we have* $\frac{\partial C_r}{\partial\gamma_r}=\frac{-\alpha(\alpha b_p\gamma_d+c_p(1+\gamma_d))}{(1+\alpha\gamma_r+(1-\alpha)\gamma_d)^2}<0$ *and* $\frac{\partial C_d}{\partial\gamma_d}=\frac{-(1-\alpha)((1-\alpha)b_p\gamma_r+c_p(1+\gamma_r))}{(1+\alpha\gamma_r+(1-\alpha)\gamma_d)^2}<0$*, respectively, the cross-price elasticity would thus decrease as the piracy rate increases. Conversely, since we have* $\frac{\partial C_r}{\partial\gamma_d}=\frac{\alpha(b_p(1+\alpha\gamma_r)+c_p(1+\gamma_r))}{(1+\alpha\gamma_r+(1-\alpha)\gamma_d)^2}>0$ *and* $\frac{\partial C_d}{\partial\gamma_r}=\frac{(1-\alpha)(b_p(1+(1-\alpha)\gamma_d)+c_p(1+\gamma_d))}{(1+\alpha\gamma_r+(1-\alpha)\gamma_d)^2}>0$*, respectively, the cross-price elasticity of one channel would thus increase as the piracy rate of its competitor channel increases.*

A.9. Proof of Proposition 6

Suppose that $\gamma_r=\gamma_d=\gamma$*, and the service levels of the two channels are the same, the difference between the equilibrium prices of the two channels is given as.*

$$P_r^*-P_d^*=\Big(a(\alpha-(1-\alpha))\big(2(1+\gamma)b_p+(1+\gamma)c_p\big)+(1+\theta^*)((W_r-W_d)\\\Big((1+\gamma)b_pc_p-(1+\gamma)^2c_p^2+2b_p^2+2\alpha(1-\alpha)\gamma^2b_p^2\Big)\\+b_p^2\gamma\Big(\alpha W_d-(1-\alpha)W_r+\alpha^2W_d-(1-\alpha)^2W_r\Big)\Big)\Big)\Big(3c_p^2(1+\gamma_r)(1+\gamma_d)\\+b_pc_p(8+(3+5\alpha)\gamma_r+(8-5\alpha+3\gamma_r)\gamma_d)+b_p^2(4+4\alpha\gamma_r+(1-\alpha)(4+3\alpha\gamma_r)\gamma_d)\Big)^{-1}.$$

It can be observed that when $b_p>c_p$*, we can have* $P_r^*-P_d^*>0$ *as* $\frac{\alpha}{1-\alpha}>\frac{W_r}{W_d}\geq1$*. Similarly, we can have* $P_r^*-P_d^*<0$ *as* $\frac{\alpha}{1-\alpha}<\frac{W_r}{W_d}\geq1$*.*

A.10. Proof of Proposition 7

Suppose that $W_r = W_d = W$, *and the service levels of the two channels are the same, the difference in the equilibrium prices is given as.*

$$
\begin{aligned}
P_r{}^* - P_d{}^* = {} & (a\alpha(1-\alpha)b_p(\gamma_d-\gamma_r) + ac_p((\alpha-(1-\alpha)) + (\alpha\gamma_r-(1-\alpha)\gamma_d)) \\
& + 2ab_p\left((\alpha-(1-\alpha)) + \left(\alpha^2\gamma_r-(1-\alpha)^2\gamma_d\right)\right) + (1+\theta^*)W \\
& \left(2c_pb_p + b_p{}^2\right)((\alpha\gamma_r-(1-\alpha)\gamma_d) + (\gamma_d-\gamma_r) + (\alpha-(1-\alpha))\gamma_r\gamma_d)) \\
& (3c_p{}^2(1+\gamma_r)(1+\gamma_d) + b_pc_p(8 + (3+5\alpha)\gamma_r + (8-5\alpha+3\gamma_r)\gamma_d) \\
& + b_p{}^2(4 + 4\alpha\gamma_r + (1-\alpha)(4+3\alpha\gamma_r)\gamma_d)\Big)^{-1}.
\end{aligned}
$$

It can be observed that $P_r{}^* - P_d{}^* > 0$, *when* $\frac{\alpha}{1-\alpha} > \frac{\gamma_d}{\gamma_r} > 1$.

A.11. Proof of Proposition 8

When$\gamma_r = \gamma_d = 0$, $\alpha = 1 - \alpha$, *and* $S_r = S_d$, *the difference in the two retail prices is given as* $P_r{}^* - P_d{}^* = \frac{(W_r-W_d)(b_p+c_p)(2b_p+c_p)(1+\theta^*)}{4(b_p+c_p)^2-c_p{}^2}$. *It is obvious that when* $W_d > W_r$ *we can have* $P_d{}^* > P_r{}^*$, *while when* $W_d = W_r$ *we can have* $P_d{}^* = P_r{}^*$, *and when* $W_d < W_r$ *we have* $P_d{}^* < P_r{}^*$, *i.e., the retail price would increase as the wholesale price rises.*

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