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Decentralization or Integration: Distribution Channel Selection under Environmental Taxation

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Decentralization or Integration: Distribution Channel Selection under Environmental Taxation

Abstract

This study reveals that the environmental tax gets less stringent when the manufacturer's distribution channel becomes more decentralized. Contrary to the classic double marginalization problem, the first implication is that a monopolistic manufacturer benefits from decentralization when its technology is sufficiently polluting. Secondly, with two competing manufacturers, both are more likely to decentralize in equilibrium when their technologies are more polluting. Under certain conditions, decentralized manufacturers may enjoy higher profits thanks to tax cuts without affecting social welfare or consumer surplus. Various extensions of the base models confirm the robustness of the analytical results.

Keywords: Channel selection; environmental tax; supply chain management; game theory.

1. Introduction

The development of global economy has given rise to many environmental issues. For instance, climate change is one of the most important environmental problems spurring numerous discussions from both practitioners and academia. Furthermore, air pollution, water pollution and solid wastes, among many others, also cause serious environmental deterioration without proper care and intervention. Confronted with such environmental issues, governments have implemented various policies to curb pollution. In particular, environmental taxation, which directly follows the "Polluter-Pays Principle", has been strongly supported by most OECD and EU countries (Morin and Orsini 2015).

Taking carbon taxes as an example: they have been widely implemented in European countries such as Denmark, Finland, Germany, Ireland, Italy, Netherlands, Norway, Slovenia, Sweden, Switzerland and UK (Andersen 2010). As reported by the European Environment Agency (2006), taxation has been the most widely used environmental policy in Europe. In Asia, carbon taxes have been imposed by Japan and India (SBS, 2016). Specifically, Japan implemented a carbon tax in October 2012, and the tax revenue is used to subsidize clean energy and energy saving projects. In July 2010, India introduced a nationwide carbon tax of 50 rupees per metric ton of coal, which has been increased to 100 rupees per metric ton in 2014. In North America, some US states (Oregon, New York and Washington) and Canadian provinces (Alberta, British Columbia and Quebec) have implemented carbon taxes. Besides carbon taxes, there exist other forms of environmental taxes such as landfill fees and water pollution taxes (OECD 2001).

In this paper, we refer to environmental taxes as generic environment-related taxes imposed on industrial pollution such as air pollution, water pollution and landfill wastes. We focus on discussing how distribution channel structures vary under such environmental taxation in the context of supply chain management. It is well-known that channel decentralization suffers from double marginalization (Spengler 1950). We attempt to reveal a benefit of decentralization under endogenous environmental tax policies, where the government sets a tax rate to maximize social welfare. We aim to address the following research questions: How does the government's taxation policy vary under different distribution channel structures? Do distribution channel strategies change when the government imposes an environmental tax? What is the impact of environmental taxation on the equilibrium channel strategies under supply chain competition? How do competition intensity and technology polluting level affect distribution channel structures?

The main findings are as follows. The environmental tax becomes less stringent when the distribution channel becomes more decentralized. The reason is that a more decentralized channel tends to produce less due to double marginalization, and thereby is less polluting. This has important implications on manufacturers' channel strategies. First, contrary to the classic double marginalization problem, a monopolistic manufacturer can benefit from decentralization when its technology is sufficiently polluting. Second, with two competing manufacturers, both are more likely to decentralize in equilibrium when their technologies are more polluting. Moreover, manufacturers' higher profits under decentralization stem from the tax cut for the less polluting industry structure, which does not affect social welfare or consumer surplus as long as their technologies are polluting enough that environmental taxation remains necessary.

The rest of the paper is organized as follows. Section 2 reviews the previous literature related to this paper. Section 3 analyzes distribution channel strategies in a single supply chain. Section 4 presents extensions and discussions with linear environmental damage, integration efficiency, transport emission, quadratic taxation, an environmentally-friendly manufacturer, and by allowing subsidies. Section 5 further extends the analysis to the case of two competing supply chains. Section 6 concludes the paper.

2. Related Literature

Two streams of literature are closely related to our research, the first stream on supply chain channel design, and the second stream on environmental policy and market structure. Extensive research has been carried out on supply chain channel design. The pioneering work of McGuire and Staelin (1983) revealed that intermediaries can serve as competition buffers, i.e., decentralization mitigate product market competition. In equilibrium, they showed that the integrated channels always occur and the decentralized channels arise when the products are highly substitutable. Moorthy (1988) revisited channel design and found that the equilibrium channel strategies do not depend on demand substitution (as in McGuire and Staelin (1983)) or complementarity, but depend on whether the price decisions are strategic substitutes or complements at both channel levels.

Building upon the aforementioned research, Bhardwaj and Balasubramanian (2005) generalized the work of McGuire and Staelin (1983) with managerial incentives and found that mixed channels can also arise in equilibrium. Cao et al. (2010) extended the model of McGuire and Staelin (1983) by adding demand uncertainty. Anderson and Bao (2010) compared integrated and decentralized channels and focused on the effect of the number of supply chains. Considering upstream collusion, Piccolo and Reisinger (2011) showed that the discount factor can affect the manufacturers' channel structures. Unlike these studies, we examine channel strategies when the government imposes an environmental tax on the production of the manufacturer(s). Our research reveals that environmental taxes can significantly change the equilibrium channel strategies.

Some studies discussed channel strategies with non-price competition. With quality competition, Zhao et al. (2009) found that both manufacturers only choose integration in equilibrium. Liu and Tyagi (2011) showed that product positioning competition can significantly relax the ensuing price competition and make the retailers decentralize upward in equilibrium. Considering displayed-quantity competition, Zhou and Cao (2014) demonstrated that various channel structures can arise in equilibrium. Instead of adding non-price competition, we concentrate on the effect of environmental taxation on distribution channel design. We find that, even in a single supply chain, the manufacturer benefits much more from decentralization than from integration when its technology is sufficiently damaging to the environment. Furthermore, with two competing supply chains, we demonstrate that the manufacturers are more likely to decentralize in equilibrium when their technologies are more environmentally damaging.

Within a single supply chain, Desai et al. (2004) and Arya and Mittendorf (2006) also found that a manufacturer can benefit from channel decentralization. They examined channel strategies in a multi-period setting where the time-inconsistency problem can be alleviated by decentralization. Differing from these two studies, we show that, even in a single period, the manufacturer's profit from the decentralized channel can be significantly higher than that from the integrated channel under environmental taxation. Some other studies focused on dual-channel supply chain design, including Balasubramanian (1998), Chiang et al. (2003), Cattani et al. (2006), Arya et al. (2008), Xu et al. (2010), Xia et al. (2013), and Pun (2013). Unlike these studies, we concentrate on single-channel distribution strategies.

The second branch of literature related to this paper is on environmental policy and market structure, dating back to Lee (1975) and Smith (1976), which revealed that market structure has an important effect on the efficiency of environmental taxation. Following their works, many other studies revisited the relationship between market structure and environmental taxation. Oates and Strassmann (1984) examined the efficiency of environmental taxation in a mixed market consisting of various types of organizations such as private and public firms. Conrad and Wang (1993) compared pollution taxes and abatement subsidies under three market structures: perfect competition, oligopolistic competition and a dominant firm with a competitive fringe. More relevantly, Markusen et al. (1993) discussed environmental taxation in a two-market, two-firm model where firms locate their plants endogenously. They demonstrated that the social cost can be very high if environmental taxation ignores market endogeneity. With oligopolistic competition, Katsoulacos and Xepapadeas (1996) found that the optimal emissions tax could exceed marginal environmental damage under endogenous market structure. Similarly, Lee (1999) revisited environmental taxation under an endogenous oligopolistic market structure and found that the equilibrium number of firms in a market may differ from the socially optimal number of firms.

Althammer and Bucholz (1999) discussed how market structures impact the second-best choice of the environmental tax. Cato (2010) proposed a three-part environmental tax policy in an endogenous market structure and found that it works effectively. Sheu (2011) examined the impact of government financial intervention on cooperative negotiations between manufacturers and reverse-logistics suppliers using an asymmetrical Nash bargaining game. Hafezalkotob (2017) developed a model of competition and cooperation between two green supply chains, and found that the government can reconcile social, financial, and environmental objectives with an appropriate tariff mechanism. For a comprehensive review on environmental policy and green supply chains, readers are referred to Carraro et al (2013) and Gunasekaran et al (2015). Our research departs from the aforementioned works from two aspects. First, we examine environmental taxation with vertical market structures in supply chains, while they all focused on horizontal market structures. Second, we study distribution channel strategies, while they examined other issues like plant locations and the number of firms in a market. Park et al. (2015) discussed whether the supply chain structure and social welfare vary with carbon fees charged. They studied supply chain design in terms of how many retailer stores to open for the retailer(s) in a horizontal market, while we focus on vertical distribution channel design with regard to whether the manufacturer(s) will vertically integrate or decentralize under endogenous environmental taxation.

3. Channel strategies in a single supply chain

This section starts with a list of notations used in the subsequent analyses.

Table 1. Notations for the case of a single supply chain.

Variable and parameter	**Definition**
q	Production quantity
p	The retail price of the product
t	Environmental tax rate per unit
d	The coefficient measuring how environmentally damaging the manufacturer's technology is, with a higher d indicating a more polluting technology.
α	The market potential.
w	The wholesale price of the products
β	The coefficient capturing demand sensitivity
SW	Social welfare incorporating environmental externalities

Next, we consider a single-product supply chain with the stylized inverse demand function

$$p(q) = \alpha - \beta q,$$

where p is the market clearing price under quantity q, α is the price cap, and β measures the sensitivity of retail price to demand change. Based on this, we obtain the demand function as

$$q(p) = \frac{\alpha - p}{\beta}. \tag{1}$$

This demand function is derived based on the well-known quadratic utility, which is consistent with the law of diminishing marginal utility (Spence, 1976). Without loss of generality, the manufacturer's marginal production cost is normalized to zero.

Based on Spence (1976), Pal and Saha (2015), and the references therein, we can derive social welfare, which is the sum of consumer surplus and the profit of the firm(s), and incorporates the manufacturer's production externalities as

$$SW = \overbrace{\int_0^q (\alpha - \beta x)dx}^{\text{Traditional social welfare}} - \overbrace{\frac{1}{2}dq^2}^{\text{Environmental damage}} = \overbrace{\left(\alpha q - \frac{1}{2}\beta q^2\right)}^{\text{Traditional social welfare}} - \overbrace{\frac{1}{2}dq^2}^{\text{Environmental damage}} \quad (2)$$

where the first term is the traditional social welfare, equal to the sum of firm profits ($\left(\alpha - \beta q\right)q$) and consumer surplus ($\frac{1}{2}\beta q^2$) and the second term measures environmental damage cost resulting from the manufacturer's production emission. The coefficient $d \geq 0$ is related to how environmentally damaging the manufacturer's technology is, with a higher d indicating a more polluting technology. The quadratic function of environmental damage characterizes diminishing returns as it shows that subsequent production is progressively more damaging to the environment. From a theoretical perspective, this treatment is consistent with previous literature such as Poyago-Theotoky and Teerasuwannajak (2002), Poyago-Theotoky (2007), and Ouchida and Goto (2014). On the other hand, to examine the robustness of our results, Section 4.1 examines the case with a linear environmental damage cost.

The following analysis is performed in a game-theoretic setting and the decision sequence is shown in Figure 1. First, the manufacturer decides whether to adopt an integrated or a decentralized channel. Next, the government chooses a per unit tax rate to be imposed on the manufacturer's production. Subsequently, the manufacturer chooses a retail price in the integrated channel or a wholesale price in the decentralized channel given the government's tax rate decision. In the decentralized channel, there will be another stage in which the retailer decides the retail price, conditional on the wholesale price and tax rate decisions.

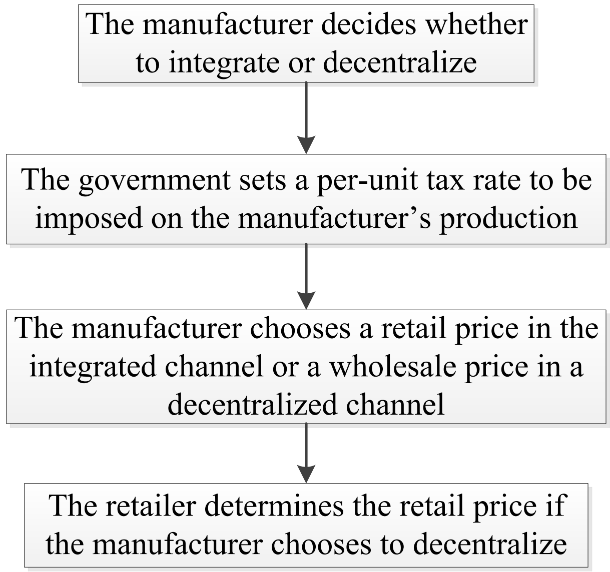


Figure 1. Decision sequence with a single supply chain

3.1. When the manufacturer chooses an integrated channel

We first consider the integrated channel, where the manufacturer directly sells its product to the end market. Given the decision sequence, the game is solved backward to ensure sub-game perfection. Thus, we start from the manufacturer's decision. Given the government's per unit tax rate t, the manufacturer solves the following profit-maximization problem

$$\max_{p} \Pi_M^I = (p-t)q(p) \tag{3}$$

where the superscript "*I*" denotes the integrated channel in this benchmark model and the subscript "*M*" indexes the manufacturer. Solving problem (3) yields the manufacturer's pricing decision

$$p^I(t) = \frac{\alpha + t}{2}. \tag{4}$$

Anticipating Eq. (4), the government's objective is to set a tax rate to maximize social welfare given by Eq. (2), yielding

$$t^I = \begin{cases} \dfrac{d-\beta}{d+\beta}\alpha, \text{ if } d > \beta \\ 0, \text{ otherwise} \end{cases}. \quad (5)$$

Mathematically, t^I is continuous in d. However, when $d < \beta$, we will have a negative tax, corresponding to a subsidy to the manufacturer. This subsidy can be interpreted from two different perspectives. From a traditional economic efficiency perspective, this subsidy is due to the manufacturer, as a monopolist, exercising its market power to produce too little. In this case, the problem at hand is not the environmental damage caused by excessive production but the economic efficiency loss caused by underproduction. It is unreasonable for the government to subsidize a monopolist who exercises its market power. Therefore, we do not consider negative tax as shown in Eq. (5). On the other hand, from an environmental protection perspective, it is natural for the government to subsidize low-polluting technology (when d is small). For instance, many countries such as the U.S., China, and Japan, are investing heavily in developing plug-in hybrid or electric vehicles (https://myelectriccar.com.au/incentives/). For this reason, the subsidy case will be discussed as an extension in Section 4.5. Here in our base model without subsidy, Eq. (5) is truncated for $d \leq \beta$. After this treatment, Eq. (5) suggests that the government would impose a tax on the product only if the manufacturer's technology is sufficiently damaging to the environment ($d > \beta$). This is consistent with many other studies such as Petrakis and Xepapadeas (2003), Fujiwara (2009), and Ouchida and Goto (2014). It is also observed that t^I increases in d, indicating that the government will set a higher tax rate for a more environmentally damaging technology. This observation is intuitive and holds for all channel structures throughout this paper.

Based on Eq. (5), we can derive the equilibrium values of the other decision variables as summarized in Table 3 in the Appendix under the "Integrated channel" column.

3.2. When the manufacturer chooses a decentralized channel

We now move on to study the decentralized channel. Under decentralization, the manufacturer distributes products through an independent retailer, who in turn sells the product to the end market. Using backward induction, we first analyze the retailer's pricing decision. Given the manufacturer's wholesale price w, the retailer solves

$$\max_{p} \Pi_R^D = (p-w)q(p), \tag{6}$$

where the superscript "*D*" denotes the decentralized channel and the subscript "*R*" denotes the retailer. Solving Eq. (6) gives the retailer's pricing decision

$$p^D(w) = \frac{\alpha + w}{2}. \tag{7}$$

Anticipating Eq. (7), the manufacturer maximizes its profit expressed by

$$\max_{w} \Pi_M^D = (w-t)q^D\left(p^D(w)\right). \tag{8}$$

Substituting Eq. (7) into Eq. (8), we can express the manufacturer's profit as a function of its wholesale price. Solving problem (8), we obtain the manufacturer's wholesale price as

$$w^D(t) = \frac{\alpha + t}{2}. \tag{9}$$

Eq. (9) suggests that the manufacturer actually transfers half of the environmental tax onto the retailer, indicating that the retailer is implicitly taxed under this base model.

Knowing the responses of the manufacturer and the retailer as in Eq. (7) and Eq. (9), the government sets a tax rate to maximize social welfare expressed by Eq. (2), resulting in

$$t^D = \begin{cases} \dfrac{d-3\beta}{d+\beta}\alpha, \text{ if } d > 3\beta \\ 0, \text{ otherwise} \end{cases}. \tag{10}$$

Following the same line of reasoning as Eq. (5), this base model truncates the negative tax (or subsidy) when $d < 3\beta$, and the subsidy case will be discussed as an extension in Section 4.6.

Based on Eq. (10), we obtain the equilibrium values of the other decision variables as shown in Table 3 in Appendix under the "Decentralized channel" column.

Comparing Eq. (5) and Eq. (10) regarding the tax rate, we readily have

Proposition 1. The government's optimal tax policy with a single supply chain satisfies

(a). If $d \le \beta$, then $t^I = t^D = 0$.

(b). If $\beta < d \le 3\beta$, then $t^I > t^D = 0$.

(c). If $d > 3\beta$, then $t^I > t^D > 0$.

Proof. A direct comparison of the tax rates under decentralization and integration in Table 3 confirms the relationships given in this proposition.

Proposition 1 suggests that the government's environmental tax policy critically depends on the manufacturer's channel choices and how environmentally damaging the manufacturer's technology is. Specifically, if the manufacturer's technology is sufficiently low-polluting ($d \le \beta$), the government will not impose an environmental tax on the manufacturer, regardless of the channel structures (Proposition 1(a)). Next, if the manufacturer's technology is intermediately polluting, as in Proposition 1(b), the government will impose a tax on the integrated manufacturer but not on the decentralized manufacturer. This is because, compared with the decentralized channel, the integrated manufacturer tends to produce more products, resulting in more environmental damage. Thus, a tax is necessary to curb the production to protect the environment. In contrast, the decentralized channel is exempted from taxation because double marginalization serves as a self-restraining vehicle and restricts the production at a low and less polluting level. Simply speaking, *the decentralized channel is less polluting because of double marginalization*. Finally, Proposition 1(c) suggests that the government always imposes a tax on the manufacturer under both the integrated and the decentralized channels if its technology is highly detrimental to the environment. Note that, although both channels are taxed, the integrated channel bears a higher tax rate than the decentralized channel.

In summary, under endogenous environmental taxation, the manufacturer enjoys a lower tax rate under decentralization than under integration when the production technology is sufficiently damaging to the environment. Next, we will show that this benefit of decentralization has a critical effect on the manufacturer's channel strategy.

Based on the manufacturer's profits shown in Table 3 in Appendix, we obtain:

Proposition 2. Under endogenous environmental taxation with a single supply chain, we have

(a). If $d \le \beta$, then $\Pi_M^D < \Pi_M^I$.

(b). If $\beta < d \le 3\beta$, then $\Pi_M^D > \Pi_M^I$ if $\left(2\sqrt{2}-1\right)\beta < d \le 3\beta$, and $\Pi_M^D \le \Pi_M^I$ otherwise, with equality holding at $d = \left(2\sqrt{2}-1\right)\beta$.

(c). If $d > 3\beta$, then $\Pi_M^D = 2\Pi_M^I$.

Proof. See Appendix.

Proposition 2(a) is a benchmark case with no environmental tax on low-polluting technology. This standard result states that the decentralized channel suffers from double marginalization, leading to lower manufacturer profit. We place it here just to highlight the effect of environmental taxation in the remaining parts.

Proposition 2(b) suggests that, when the technology is of an intermediately polluting range, the manufacturer profits more by choosing decentralization (integration) if the technology is in the higher-polluting (lower-polluting) end of this range. The reason is that, for intermediately polluting technology, the government treats the two channels differently by imposing an environmental tax on the integrated channel while leaving the decentralized channel tax free.

From the manufacturer's perspective, integration improves efficiency but incurs an environmental tax, while decentralization suffers from double marginalization but enjoys tax exemption. When the technology is relatively low-polluting ($\beta < d \le \left(2\sqrt{2}-1\right)\beta$), efficiency improvement for the integrated channel is more than enough to offset the environmental tax. On the other hand, if the technology is sufficiently damaging to the environment ($\left(2\sqrt{2}-1\right)\beta < d \le 3\beta$), decentralization rakes in more profit for the manufacturer as the tax saving outweighs the efficiency loss caused by double marginalization. This result implies that, under endogenous environmental taxation, the manufacturer's channel choice does not follow the conventional case as it is contingent upon how environmentally damaging its technology is.

In Proposition 2(c), the manufacturer always prefers the decentralized to the integrated channel when its technology is highly detrimental to the environment ($d > 3\beta$). More precisely, the manufacturer's profit from the decentralized channel is twice that from the integrated channel. The reason, again, is that, under endogenous environmental taxation, the manufacturer benefits from a lower tax rate under decentralization, and this tax saving effect outweighs the efficiency loss when the technology is highly polluting.

In summary, our analyses suggest that, under endogenous environmental taxation, a monopolistic manufacturer should sell through a private retailer if its technology is sufficiently polluting. This result relies on a decision sequence that the government sets the tax rate conditional on the manufacturer's channel choice, i.e., the manufacturer is the leader and the government is the follower. This decision sequence can be justified from three angles:

First, it is common to observe that governments adjust various policies based on industry structure in practice (Aalders and Wilthagen, 1997; Tompkin, 2001; Braithwaite, 2007; Braithwaite et al., 2007). For instance, Aalders and Wilthagen (1997) argued that, in environmental regulation, reflexive administrative laws can be feasible and desirable, calling for a "negotiating government". Using taxation data, Braithwaite (2007) established normative and explanatory arguments in favor of responsive regulation in a taxation context. Similarly, empirical taxation data showed that responsive regulation is a viable way to achieve effective regulatory outcome. Furthermore, in food safety regulation, Tompkin (2001) reported that many interactions between the government and industry contribute to improved safety in food supply. Corresponding to our model setting, different channel structures can be treated as different industry structures with the government adopting responsive taxation contingent upon the manufacturers' channel choice.

Second, the manufacturer's channel choice is typically a longer-term, more strategic decision than the government's tax rate setting, especially when the government follows a responsive regulation strategy. That is, compared with the manufacturer's changing its channel structure, if the legislation allows the government to adjust the environmental tax rate relatively expeditiously (especially for lowering the tax rate), then it is likely that the government will re-optimize the tax rate in response to a change in the industry structure.

The third point supporting our decision sequence assumption is that the government (from a social welfare maximization perspective) is indifferent in the manufacturer's channel choice if the technology is sufficiently polluting. To see this, let us compare the integrated and the decentralized channels in Table 3 in Appendix. For $d > 3\beta$, the retail price and quantity, and the social welfare are all the same under the two channels. As a matter of fact, they are all at the first-best level. Note that social welfare herein consists of tax revenue, industry profit and consumer surplus. Higher industry profit under decentralization is simply due to a tax revenue transfer from the government compared to the integrated channel structure. The reduction in tax revenue is counterbalanced by the increased profit, thereby resulting in the same first-best social welfare for both channels. This means that the government has no incentive to be the leader in the game: by setting the tax rate conditional on the manufacturer's channel choice, the first-best social welfare is still attainable. In addition, if the manufacturer decentralizes, the government achieves the first-best social welfare with a lower tax rate, a higher industry profit, and the same consumer surplus, and thus may gain higher public support.

The above observation also implies that, the manufacturer's higher profit under decentralization stems from the tax cut for a less polluting industry structure, which does not affect social welfare or consumer surplus if its technology is sufficiently polluting. When the manufacturer's technology is not so polluting ($d < 3\beta$), it can be verified that social welfare is lower under decentralization. In this case, the production quantity under decentralization is lower than the first-best level, which means that, the problem at hand is no longer environmental damage caused by excessive production but the economic efficiency loss caused by the firms' market power. Because we do not consider government subsidy (negative tax) in the base case to improve economic efficiency, the first-best social welfare is no longer attainable when the technology is low-polluting ($d < 3\beta$ under decentralization, or $d < \beta$ under integration). In conclusion, the manufacturer's higher profit under decentralization may deteriorate social welfare and consumer surplus only if its technology is low-polluting enough that environmental protection is no longer the focal issue.

Our results can also be interpreted from a prescriptive perspective: For a heavily polluting industry, the decentralized channel structure is a better choice because it offers a higher industry profit under the same environmental protection goal (the same production level, social welfare and consumer surplus). Therefore, the government should set its tax policy to induce the manufacturer to decentralize. In this regard, the aforesaid "decision sequence assumption" becomes irrelevant: if the government is the leader, it should announce that the tax rate will be conditional on the manufacturer's channel choice, leading to the same result as presented earlier.

4. Extensions and Discussions

This section discusses different extensions for the base model to examine the robustness of our analytical results in Section 3.

4.1. Extension with a linear environmental damage cost

The base model adopts a quadratic function to gauge marginally increasing environmental damage cost. In reality, it is common that this cost may assume a linear form. In addition, linear cost has been empirically examined and widely adopted in theoretical studies (Mäler, 1991; Richard, 1995). As such, our first extension considers a linear instead of a quadratic environmental damage cost function. In this case, social welfare is expressed as $SW=\left(\alpha q-\frac{1}{2}\beta q^2\right)-dq$. Similarly, the equilibrium result is obtained as shown in Table 4 in Appendix. In the following analysis, it is assumed that $d<\alpha$ to ensure that the equilibrium quantity is positive and the retail price is larger than the wholesale price under decentralization. Given this assumption, we can easily extend Propositions 1 and 2 as follows by examining the equilibrium outcomes in Table 4. Here we assume the superscript "*DL*" denotes the decentralized channel and "*IL*" the integrated channel with a linear environmental damage cost.

Lemma 1. Comparing the tax rates under integration and decentralization in Table 4, we have (a). If $d\le\frac{\alpha}{2}$, then $t^{IL}=t^{DL}=0$. (b). If $\frac{\alpha}{2}<d\le\frac{3\alpha}{4}$, then $t^{IL}>t^{DL}=0$. (c). If $d>\frac{3\alpha}{4}$, then $t^{IL}>t^{DL}>0$.

Proposition 3. Under a linear environmental damage cost, we have (a). If $d \le \frac{1}{2}\alpha$, then $\Pi_M^{DL} < \Pi_M^{IL}$.

(b). If $\frac{1}{2}\alpha < d \le \frac{3}{4}\alpha$, then $\Pi_M^{DL} > \Pi_M^{IL}$ if $\left(1-\frac{\sqrt{2}}{4}\right)\alpha < d \le \frac{3}{4}\alpha$, and $\Pi_M^{DL} \le \Pi_M^{IL}$ otherwise, with equality if and only if $d = \left(1-\frac{\sqrt{2}}{4}\right)\alpha$.

(c). If $d > \frac{3}{4}\alpha$, then $\Pi_M^{DL} = 2\Pi_M^{IL}$.

Proof. See Appendix.

Lemma 1 and Proposition 3 clearly demonstrate that the structural insights obtained in Propositions 1 and 2 remain valid under a linear damage cost: when environmental damage is sufficiently small ($d \le \frac{1}{2}\alpha$), both channels are left untaxed and the manufacturer achieves higher profitability under integration; when environmental damage is in the middle range ($\frac{1}{2}\alpha < d \le \frac{3}{4}\alpha$), the government imposes an environmental tax on the integration channel, but leaves the decentralization channel untaxed. This tax policy allows the manufacturer to close in its profitability gap under decentralization with that under integration and eventually achieve a higher profit under decentralization if $d > \left(1-\frac{\sqrt{2}}{4}\right)\alpha$; when environmental damage is sufficiently large ($d > \frac{3}{4}\alpha$), both channels are taxed, but decentralization enjoys a lower tax rate. In this case, the manufacturer's profitability doubles under decentralization compared to the integration case. In comparison with the result in Propositions 1 and 2, the only difference is the change in thresholds. Therefore, replacing the quadratic environmental cost function in Eq. (2) with a linear cost does not qualitatively change our results except for shifting the threshold values.

4.2. Extension with operational efficiency under integration

In supply chain management, it is well known that vertical integration helps supply chain partners better coordinate their decisions and leads to operational efficiency gains. The second extension entertains this idea and incorporates operational efficiency into our model. More specifically, we consider the case where the integrated channel is less polluting due to more efficient operations. Mathematically, we express this integration efficiency as follows:

$$\begin{cases} SW^{DE} = \overbrace{\alpha q - \frac{1}{2}\beta q^2}^{\text{Traditional social welfare}} - \overbrace{\frac{1}{2} d q^2}^{\text{Environmental damage}} \\ SW^{IE} = \overbrace{\alpha q - \frac{1}{2}\beta q^2}^{\text{Traditional social welfare}} - \overbrace{\frac{1}{2}\eta d q^2}^{\text{Environmental damage}} \end{cases}, \tag{11}$$

where the superscript "*DE*" denotes the decentralized channel and "*IE*" the integrated channel under efficiency concerns. In Eq. (11), integration has a potential efficiency gain as expressed by $-\frac{1}{2}\eta d q^2$, where $\eta \in (0,1]$ and $\eta = 1$ corresponds to the previous benchmark case without any efficiency gain and $\eta < 1$ means less environmental damage due to integration efficiency. Based on this formulation, we obtain the equilibrium result in Table 5 in Appendix and the following result.

Lemma 2. With operational efficiency under integration, the government's optimal tax rates satisfy

(i). If $\eta > \frac{1}{3}$, (a). If $d \le \frac{\beta}{\eta}$, then $t^{IE} = t^{DE} = 0$. (b). If $\frac{\beta}{\eta} < d \le 3\beta$, then $t^{IE} > t^{DE} = 0$. (c). If $d > 3\beta$, then $t^{IE} > t^{DE} > 0$.

(ii). If $0 < \eta \le \frac{1}{3}$, (a). If $d \le 3\beta$, then $t^{IE} = t^{DE} = 0$. (b). If $3\beta < d \le \frac{\beta}{\eta}$, then $t^{DE} > t^{IE} = 0$. (c). If $d > \frac{\beta}{\eta}$, then $t^{DE} > t^{IE} > 0$.

When the operational efficiency is not so dramatic (i.e., $\eta > \frac{1}{3}$, where a lower η means a higher operational efficiency), case (i) yields the same structural insights as Proposition 1 in the base model: the government leaves both channels untaxed for sufficiently low-polluting production ($d \le \frac{\beta}{\eta}$); when the pollution level increases (a larger d), the government starts imposing an environmental tax on the integration channel and, lastly, on the decentralization channel. On the other hand, if the operational efficiency is high enough (i.e., $\eta \le \frac{1}{3}$ or η is small enough), integration enjoys a preferred environmental tax treatment as long as $d > 3\beta$.

Proposition 4. With operational efficiency under integration, we have

(a). If $0 < \eta < \frac{2\sqrt{2}-1}{3}$, then $\Pi_M^{DE} < \Pi_M^{IE}$;

(b). If $\eta > \frac{2\sqrt{2}-1}{3}$, then

(i). If $d > 3\beta$ and $\eta \ge \frac{\sqrt{2}}{2}$, then $\Pi_M^{DE} > \Pi_M^{IE}$;

(ii) If $d > 3\beta$ and $\eta < \frac{\sqrt{2}}{2}$, then $\Pi_M^{DE} > \Pi_M^{IE}$ for $d < \frac{\sqrt{2}-1}{1-\sqrt{2}\eta}\beta$, and $\Pi_M^{DE} \le \Pi_M^{IE}$ otherwise.

(iii) If $d < 3\beta$, then $\Pi_M^{DE} > \Pi_M^{IE}$ for $d > \frac{\left(2\sqrt{2}-1\right)\beta}{\eta}$, and $\Pi_M^{DE} \le \Pi_M^{IE}$ otherwise.

Proof. See Appendix.

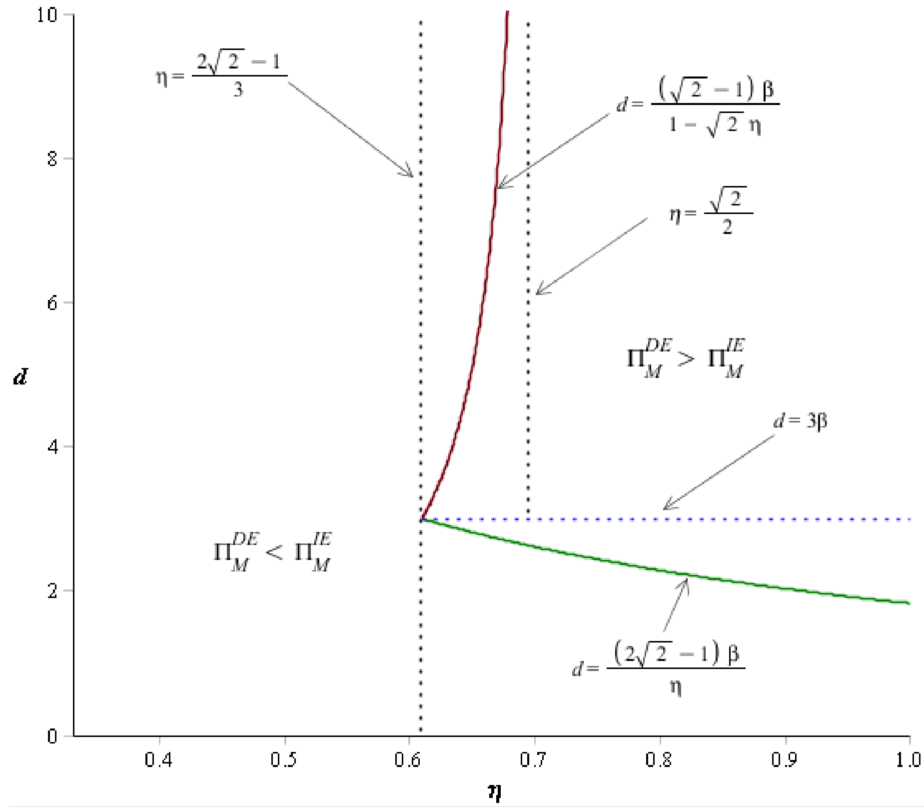


Figure 2. Manufacturer profit comparison with operation efficiency under integration

Proposition 4 is visually displayed in Figure 2 ($\beta = 1$). It is clear from the figure that decentralization offers a higher profit for the manufacturer when environmental damage is high (a larger d) and integration efficiency is not so significant (a larger η). On the other hand, if the integration efficiency gain is sufficient (i.e., $\eta < \frac{2\sqrt{2}-1}{3}$), then the manufacturer always achieves better profitability under integration regardless of environmental damage *d*.

4.3. Extension with transport emission

The base model considers only emission resulting from the production process. When a retailer is present in a decentralized system, it is natural that more transportation activities will be involved in serving customer demand and, hence, more transport emission will be incurred. As such, the third extension here considers emission from transportation. By incorporating environmental damage from transport emission, we have

$$\begin{cases} SW^{DT} = \overbrace{\alpha q - \frac{1}{2}\beta q^2}^{\text{Traditional social welfare}} \overbrace{-\frac{1}{2}\left(d + d^T\right) q^2}^{\text{Environmental damage}} \\ SW^{IT} = \overbrace{\alpha q - \frac{1}{2}\beta q^2}^{\text{Traditional social welfare}} \overbrace{-\frac{1}{2}\left(d + \eta^T d^T\right) q^2}^{\text{Environmental damage}} \end{cases}, \tag{12}$$

where the superscripts "*DT*" and "*IT*", respectively, refer to the decentralized and integrated channel under transport emission, d^T is the coefficient of damage due to transportation in addition to production. Same as before, $\eta^T \in (0,1]$ indicates the integrated channel is more efficient in transportation. Based on the equilibrium result in Table 6 in Appendix, we can derive Proposition 5 as follows.

Lemma 3. With transport emission, the government's optimal tax rates are related as:

(i). If $2\beta + \eta^T d^T - d^T > 0$, (a). If $d \le \beta - \eta^T d^T$, then $t^{IT} = t^{DT} = 0$. (b). If $\beta - \eta^T d^T < d \le 3\beta - d^T$, then $t^{IT} > t^{DT} = 0$. (c). If $d > 3\beta - d^T$, then $t^{IT} > t^{DT} > 0$.

(ii). If $2\beta + \eta^T d^T - d^T \le 0$, (a). If $d \le 3\beta - d^T$, then $t^{IT} = t^{DT} = 0$. (b). If $3\beta - d^T < d \le \beta - \eta^T d^T$, then $t^{DT} > t^{IT} = 0$. (c). If $d > \beta - \eta^T d^T$, then $t^{DT} > t^{IT} > 0$.

Note that $2\beta + \eta^T d^T - d^T > 0$ can be rearranged as $\eta^T > \frac{d^T - 2\beta}{d^T}$, so case (i) corresponds to the scenario that integration does not offer a significant transport emission gain. In this case, if the aggregate emission from production and transport（$d + \eta^T d^T$ under integration or $d + d^T$ under decentralization） is below the corresponding threshold (β under integration or 3β under decentralization), the government will leave the channel untaxed. The structural insights in Proposition 1 remain valid. Similarly, case (ii) corresponds to a sufficiently high transport efficiency gain due to integration. In this case, as long as the aggregate emission from production and transport under decentralization is high enough (i.e., $d + d^T > 3\beta$), the tax rate for the integration channel is always lower than that for the decentralization channel.

Proposition 5. With transport emission, we have the following result.

(a). If $\eta^T > \max\left\{\frac{d^T - 2\left(2-\sqrt{2}\right)\beta}{d^T}, 0\right\}$, then $\Pi_M^{DT} > \Pi_M^{IT}$ for $d > \left(2\sqrt{2}-1\right)\beta - \eta^T d^T$, and $\Pi_M^{DT} \le \Pi_M^{IT}$ otherwise.

(b). If $0 < \eta^T \le \frac{d^T - 2\left(2-\sqrt{2}\right)\beta}{d^T}$, then $\Pi_M^{DT} > \Pi_M^{IT}$ for $d > \left(1+\sqrt{2}\right)\left(1-\sqrt{2}\eta^T\right)d^T - \beta$, and $\Pi_M^{DT} \le \Pi_M^{IT}$ otherwise.

Proof. See Appendix.

Proposition 5 can be visually illustrated by Figure 3 ($\beta = 1$). It is clear that, under transport emission consideration, the decentralization channel arises as a better choice for the manufacturer in terms of its profitability only if the environmental damage is sufficiently large (d is large enough). The specific threshold for d depends on transportation emission d^T and integration efficiency in transportation η^T.

4.4. Extension with a quadratic tax

In this extension, we introduce the tax as a quadratic function to make it consistent with the quadratic form of the environmental damage term. By entertaining different functional forms of the tax cost, we wish to examine how robust the main analytical results are. Specifically, we adopt the tax term $\frac{1}{2}tq^2$. Following the same solution procedure, we can obtain all the equilibrium results in Table 7 in Appendix. The superscripts "*DQ*" and "*IQ*" below refer to the decentralized and integrated channel under quadratic taxation, respectively. Based on the equilibrium results, we have

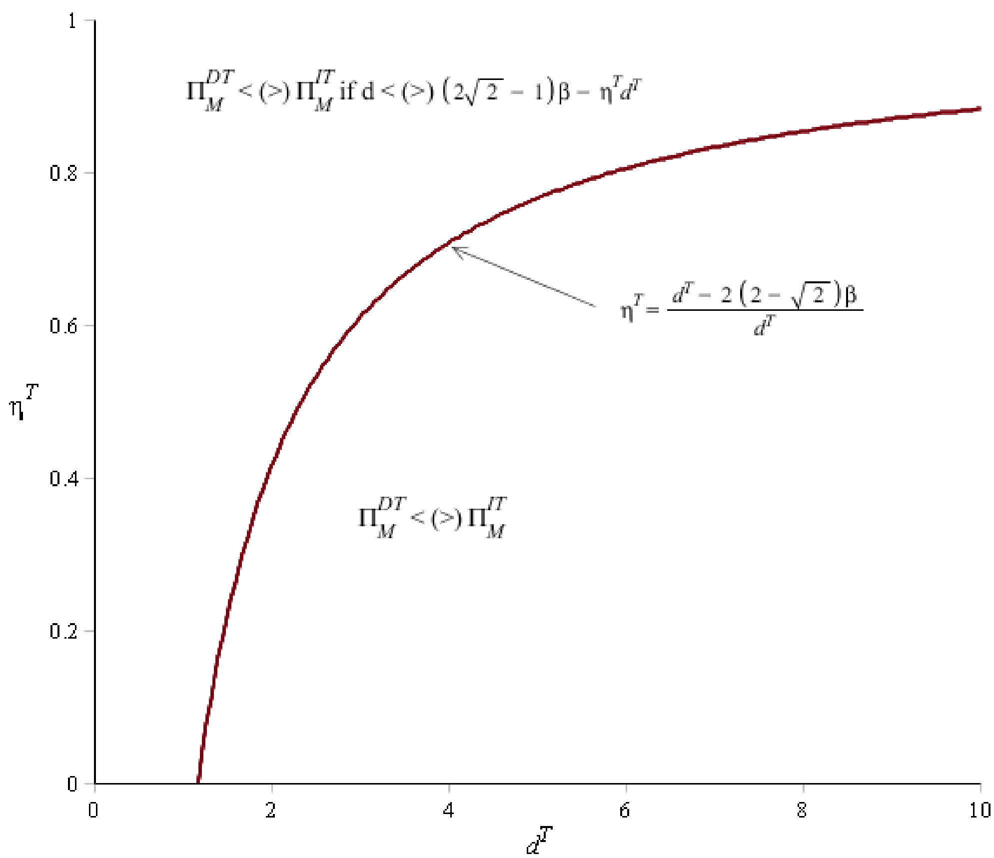


Figure 3. Profit comparisons with transport emission

Lemma 4. With a quadratic tax term, comparing the tax rates in Table 7 yields: (a). If $d \le \beta$, then $t^{IQ} = t^{DQ} = 0$. (b). If $\beta < d \le 3\beta$, then $t^{IQ} > t^{DQ} = 0$. (c). If $d > 3\beta$, then $t^{IQ} > t^{DQ} > 0$.

Lemma 4 clearly demonstrates that the main results of Proposition 1 are directly carried over to the quadratic taxation case.

Proposition 6. With a quadratic tax term, we obtain

(a). If $d \le 3\beta$, then $\Pi_M^{DQ} < \Pi_M^{IQ}$.

(b). If $d > 3\beta$, then $\Pi_M^{DQ} = \Pi_M^{IQ}$.

Proof. See Appendix.

Proposition 6 demonstrates that main conclusion on the manufacturer's channel selection relies on the linear tax function. This is fine as linear taxes and charges on pollution emission are indeed very common in practice. For instance, the Clean Air Act Amendments of 1990 in America require that States impose fees on air emission, and set the minimum presumptive level for such fees at $25 per ton of emissions of air toxics and criteria air pollutants. Similarly, New Mexico, for example, levies fees of $150 per ton for air toxics and $10 per ton for criteria pollutants. Regarding solid wastes, cities such as Portland, Lansing and San Jose have also implemented charges proportional to the volume of emission (U.S. Environmental Protection Agency, 2004). On the other hand, the general trend of potential benefit of decentralization still holds true under quadratic taxes as it helps the manufacturer to close in the profitability gap due to efficiency loss when environmental damage is large enough ($d > 3\beta$), but this benefit is insufficient to make the decentralization channel outperform the integration channel.

4.5. Extension with an environmentally-friendly manufacturer

In the base model in Section 3, the manufacturer is only concerned with profit maximization. As observed in business practice and recent research, corporations may consider other objectives such as social and environmental performance on top of profitability (Bian et al., 2016; Ni et al., 2010, Ni and Li, 2012). Along this line of thinking, this extension incorporates the manufacturer's environmental concerns into its objective function by assigning a weight to the environmental damage as shown below:

$$\max_{p} \Pi_M^{IEn} = (p-t)q - \frac{1}{2}\mu d q^2 \text{ under integration, and}$$

$$\max_{w} \Pi_M^{DEn} = (w-t)q - \frac{1}{2}\mu d q^2 \text{ under decentralization,}$$

where the superscripts "*DEn*" and "*IEn*" below, respectively, denote the decentralized and integrated channel with environmental concerns, $\mu \in [0,1]$ represents the manufacturer's weight on the environmental performance in its goal. $\mu = 1$ means that the manufacturer gives environment a full consideration and $\mu = 0$ stands for a profit-maximizing manufacturer as given in the base model in Section 3. Equilibrium outcomes are shown in Table 8 and the tax rate and channel comparison results are derived as follows.

Lemma 5. With an environmentally-friendly manufacturer, comparing the tax rates in Table 8 leads to: (a). If $d \le \beta$, then $t^{IEn} = t^{DEn} = 0$. (b). If $\beta < d \le 3\beta$, then $t^{IEn} > t^{DEn} = 0$. (c). If $d > 3\beta$, then $t^{IEn} > t^{DEn} > 0$.

Once again, the government's tax policies with an environmentally-friendly manufacturer follow the same pattern as shown in Proposition 1 for the base model.

Proposition 7. With an environmentally-friendly manufacturer, we have

(a). If $d \le \beta$, then $\Pi_M^{DEn} < \Pi_M^{IEn}$.

(b). If $\beta < d \le 3\beta$, then $\Pi_M^{DEn} > \Pi_M^{IEn}$ for $\frac{\left(2\mu - 1 + \sqrt{4\mu^2 + 10\mu + 8}\right)\beta}{2\mu + 1} < d \le 3\beta$, and $\Pi_M^{DEn} \le \Pi_M^{IEn}$ otherwise, with equality holding at $d = \frac{\left(2\mu - 1 + \sqrt{4\mu^2 + 10\mu + 8}\right)\beta}{2\mu + 1}$.

(c). If $d > 3\beta$, then $\Pi_M^{DEn} > \Pi_M^{IEn}$.

Proof. See Appendix.

It is clear from Proposition 7 that, with an environmentally-friendly manufacturer who is concerned with both profit and environmental performance, the structural insights in Proposition 2 remain valid except for the shifted critical threshold d in Proposition 7(b) beyond which decentralization arises as the better choice. Another minor difference is that the manufacturer's profit under decentralization is no longer twice as much as that under integration when $d > 3\beta$. This result is natural given that the manufacturer now has both economic and non-economic considerations.

4.6. Discussions of the subsidy case

As illustrated in Eqs. (5) and (10) in Section 3, our base model truncates the government tax to zero when environmental damage is sufficiently small. This treatment does not allow for subsidies with a low polluting technology (when d is small). In practice, it is common to observe that governments provide subsidies to greener or less polluting technologies. For instances, consumers purchasing either plug-in hybrids or electric cars can obtain tax credits in many countries including the U.S.A. and Canada. To allow subsidies for low polluting technology, the only change is not to truncate the negative taxes (or subsidies) in the equilibrium tax expressions in Table 3. In this case, the tax rates for the integrated and decentralized channels will both be continuous and become negative (subsidies) when d is sufficiently small ($d \le \beta$ for the integrated channel and $d \le 3\beta$ for the decentralized channel). By deleting the two columns under the heading $d \le \beta$ and $d \le 3\beta$ in Table 3, one can derive the equilibrium results by allowing subsidies (Note that the equilibrium holds for any d). A direct comparison of the tax rates and the manufacturer's profitability lead to the following results:

Lemma 6. When the government offers subsidies for low polluting technology, its optimal policy with a single supply chain satisfies

(a). If $d \le \beta$, then $t^D < t^I \le 0$.

(b). If $\beta < d \le 3\beta$, then $t^D \le 0 < t^I$.

(c). If $d > 3\beta$, then $0 < t^D < t^I$.

Proposition 8. Under endogenous environmental taxation and subsidies with a single supply chain, we have $\Pi_M^D = 2\Pi_M^I$.

Lemma 6 and Proposition 8 strengthen the analytical results in Section 3: if the government offers subsidies for low-polluting technology, decentralization is always better than integration as the manufacturer doubles its profit under decentralization. The reason is clearly presented in Proposition 8: if the production is sufficiently green ($d < \beta$), both channels will receive subsidies but decentralization enjoys a higher subsidy; with a larger environmental damage ($\beta < d \le 3\beta$), the decentralization channel still receives a subsidy, but the integration channel starts paying taxes; when environmental damage is sufficiently large ($d > 3\beta$), both channels are taxed, but the decentralization channel receives a lower tax rate.

5. Channel strategies with two competing supply chains

First, additional notations to be used in this section are listed in Table 2 below.

Table 2. Notations for the case of two competing supply chains ($i, j = 1,2; i \ne j$).

Variable and parameter	Definition
q_i	Product i's quantity.
p_i	The retail price of the product i.
w_i	The wholesale price of the products
θ	The degree of substitutability between the two products ($\theta \in (0,1)$) to denote the competition level between the two supply chains
U	Social welfare without incorporating environmental externalities

We proceed to conduct our analysis of channel strategies for two manufacturers (manufacturer 1 and manufacturer 2, hereafter) within two competing supply chains (supply chain 1 and supply chain 2, correspondingly). Suppose that manufacturer 1 and manufacturer 2 produce two substitutable products, product 1 and product 2, respectively. Following Singh and Vives (1984), we employ the standard quadratic concave utility function expressed by

$$U\left(q_1,q_2\right)=\alpha\left(q_1+q_2\right)-\frac{1}{2}\beta\left(q_1^2+2\theta q_1 q_2+q_2^2\right),$$

Thus, consumer surplus after purchasing q_i units at price p_i is given by

$$CS\left(q_1,q_2\right)=U\left(q_1,q_2\right)-\left(p_1 q_1+p_2 q_2\right).$$

Maximizing $CS\left(q_1,q_2\right)$ gives

$$p_i\left(q_i,q_j\right)=\alpha-\beta\left(q_i+\theta q_j\right),\ i,j=1,2;i\neq j, \tag{13}$$

where $\alpha>0$ is the price cap, $\beta>0$ measures the sensitivity of product *i*'s price to its own demand, and $\theta\in\left[0,1\right)$ denotes the degree of substitutability between product *i* and product *j*. Note that we do not consider the homogeneous goods case ($\theta=1$) where the standard Bertrand Paradox arises and the manufacturers are indifferent in channel strategies. Without loss of generality, the manufacturers' marginal production costs and per-unit retailing costs are normalized to zero. Inversing Eq. (13), we obtain the demand functions as follows:

$$q_i\left(p_i,p_j\right)=\frac{\left(1-\theta\right)\alpha-p_i+\theta p_j}{\beta\left(1-\theta^2\right)},i,j=1,2;i\neq j. \tag{14}$$

Taking into account environmental damage, the government's objective is to maximize social welfare given by

$$SW = \overbrace{U(q_1, q_2)}^{\text{traditional social welfare}} - \overbrace{\frac{1}{2}d(q_1+q_2)^2}^{\text{environmental damage}} = \overbrace{\alpha(q_1+q_2) - \frac{1}{2}\beta(q_1^2 + 2\theta q_1 q_2 + q_2^2)}^{\text{traditional social welfare}} - \frac{1}{2}d(q_1+q_2)^2, \quad (15)$$

In Eq. (15), the first term denotes the total surplus from production and consumption, and the second term denotes environmental damage caused by the manufacturers' productions. Note that, in the second term of Eq. (15), we assume that the two manufacturers' technologies are equally damaging to the environment. As our focus is to examine the strategic implications of environmental taxation on the manufacturers' channel decision, this symmetric technology assumption helps us to examine the impact without worrying about whether it is due to the tax effect or technology difference (Fujiwara, 2009).

With two competing supply chains, the decision sequence is as follows (Figure 4). In the first stage, both manufacturers simultaneously choose between an integrated channel and a decentralized channel. Second, with the selected channel structure, the government sets a per-unit tax rate upon the manufacturers' production quantities. In the third stage, the manufacturer who chooses to decentralize sets a wholesale price. Finally, retail price competition occurs in the product market. This decision sequence, except for the government level, has been widely used in the literature (e.g., McGuire and Staelin 1983, Bhardwaj and Balasubramanian 2005, Piccolo and Reisinger 2011). As discussed earlier in Section 3, the government level is justified from three different angles: when the government is responsively regulating environmental taxation based on the manufacturers' channel structure, when manufacturers' channel choices are longer-term and more strategic decisions than the government's tax rate setting, and from a prescriptive perspective, the government as the leader *should* announce different tax rates conditional on manufacturers' channel decision. To ensure sub-game perfection, we adopt backward induction to derive the equilibrium solutions.

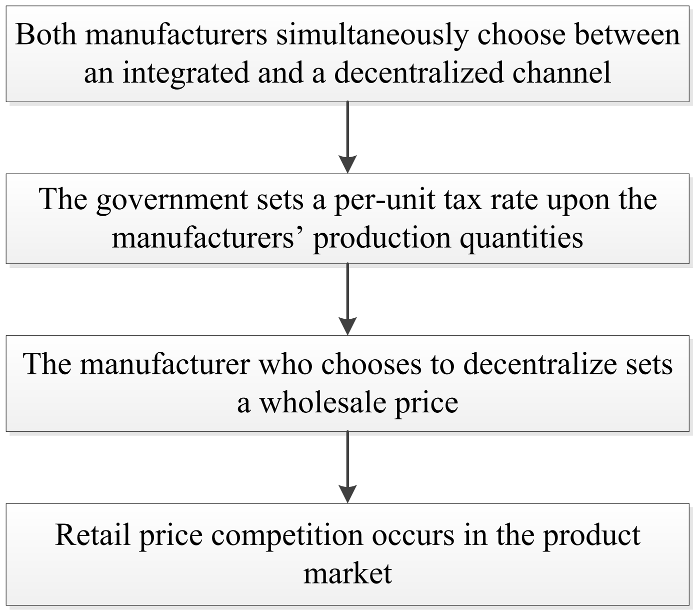


Figure 4. Decision sequence with two competing supply chains

With two competing supply chains, we use the superscript "*XY*" to indicate various channel structures, where *X* (*I* or *D*) and *Y* (*I* or *D*) indicate the channel decision by manufacturer 1 and 2, respectively, and *I* signifies the manufacturer's choice of integration and *D* means that the manufacturer chooses to distribute its product through a retailer.

In what follows, we will successively discuss each channel structure. By comparison, we can derive the final equilibrium channel structures. Channel structures "*DI*" and "*ID*" are symmetric in terms of manufacturer 1 and 2's channel choices.

5.1 Channel structure *II*

We first consider channel structure *II*, where both manufacturers 1 and 2 choose to integrate. Given the government's environmental tax rate *t*, manufacturer *i* solves the following problem

$$\max_{p_i} \Pi^{II}_{M,i}\left(p_i, p_j\right) = \left(p_i - t\right) q_i\left(p_i, p_j\right),\ i, j = 1,2; i \neq j \ , \qquad (16)$$

where the subscript "*M,i*" denotes manufacturer *i*. Substituting Eq. (14) into Eq. (16) and solving the corresponding first-order conditions (FOCs) yield the manufacturers' pricing decisions

$$p_1^{II}(t) = p_2^{II}(t) = \frac{(1-\theta)\alpha + t}{2-\theta}. \tag{17}$$

Anticipating Eq. (17), the government decides the optimal tax rate to maximize social welfare given by Eq. (15), which gives

$$t^{II} = \begin{cases} \dfrac{2d - \beta\left(1-\theta^2\right)}{2d + \beta(1+\theta)}\alpha, \text{ if } d > d^{II} \\ 0, \text{ otherwise} \end{cases}, \tag{18}$$

where

$$d^{II} = \frac{1-\theta^2}{2}\beta. \tag{19}$$

Similar to the single supply chain case, the base model does not consider subsidies and Eq. (18) is truncated for $d \le d^{II}$. From Eqs. (18)-(19), d^{II} can be viewed as a tax-free polluting threshold of the technology. The government will impose an environmental tax on channel structure *II* only if the technology is more polluting than d^{II}.

It should be mentioned here that, when $\theta = 0$, the environmental tax t^{II} given by Eq. (18) does not reduce to t^{I} given by Eq. (5). That is, when the two manufacturers' products are independent of each other, the government does not treat them as two separate monopolistic manufacturers when setting the environmental tax. The reason is simple: $\theta = 0$ only means that the two manufacturers do not interact in the product market, while their pollutions are "mutually enhancing" in causing environmental damage in the sense that each additional unit of emission by one manufacturer will be causing more marginal damage to the environment compared to the previous emission by the other manufacturer. Actually, because of this 'mutually enhancing' pollution effect, it can be verified that, setting $\theta = 0$ in t^{II} gives a more stringent environmental tax (higher tax rate and lower tax-free polluting threshold) than t^{I} does.

Based on Eq. (18), all other results are derived and summarized in Table 9 in the Appendix.

5.2 Channel structure *ID*

Next, we consider the channel structure where one manufacturer chooses integration while the other distributes its product through an independent retailer. Due to structural symmetry, we only consider the case where manufacturer 1 chooses integration whereas manufacturer 2 distributes through an independent retailer (retailer 2).

Given the government's tax rate *t* and manufacturer 2's wholesale price w_2, manufacturer 1 and retailer 2 simultaneously decide their retail prices in the end market to maximize their profits

$$\begin{cases} \max_{p_1} \Pi_{M,1}^{ID}(p_1, p_2) = (p_1 - t) q_1(p_1, p_2) \\ \max_{p_2} \Pi_{R,2}^{ID}(p_1, p_2) = (p_2 - w_2) q_2(p_1, p_2) \end{cases}. \quad (20)$$

Solving the FOCs from Eq. (20), we obtain

$$\begin{cases} p_1^{ID}(w_2, t) = \dfrac{(1-\theta)(2+\theta)\alpha + \theta w_2 + 2t}{4-\theta^2} \\ p_2^{ID}(w_2, t) = \dfrac{(1-\theta)(2+\theta)\alpha + 2w_2 + \theta t}{4-\theta^2} \end{cases}. \quad (21)$$

Expecting Eq. (21), manufacturer 2 chooses the optimal wholesale price w_2 to maximize its profit

$$\max_{w_2} \Pi_{M,2}^{ID}(w_2, t) = (w_2 - t) q_2\left(p_1^{ID}(w_2, t), p_2^{ID}(w_2, t)\right). \quad (22)$$

Solving Eq. (22) yields

$$w_2^{ID}(t) = \frac{(1-\theta)(2+\theta)\alpha + (1+\theta)(2-\theta)t}{2(2-\theta^2)}. \quad (23)$$

Given the responses in Eq. (21) and Eq. (23), the government sets the optimal tax rate to maximize social welfare expressed by Eq. (15), yielding

$$t^{ID}=\begin{cases}\dfrac{\left(6+\theta-3\theta^2\right)^2 d-\beta\left(1-\theta^2\right)\left(28+8\theta-25\theta^2-4\theta^3+6\theta^4\right)}{\left(6+\theta-3\theta^2\right)^2 d+\beta\left(1+\theta\right)\left(20+4\theta-19\theta^2-\theta^3+4\theta^4\right)}\alpha, \text{ if } d>d^{ID} \\ 0, \text{ otherwise}\end{cases}, \tag{24}$$

where d^{ID} is the tax-free polluting threshold under channel structure *ID* and is given by

$$d^{ID}=\frac{\left(1-\theta^2\right)\left(28+8\theta-25\theta^2-4\theta^3+6\theta^4\right)}{\left(6+\theta-3\theta^2\right)^2}\beta. \tag{25}$$

Based on Eq. (24), all other results are obtained and summarized in Table 10 in Appendix.

5.3 Channel structure *DD*

In this subsection, we discuss channel structure *DD*, where manufacturers 1 and 2 choose to distribute through retailers 1 and 2, respectively. Given the government's tax rate and the manufacturers' wholesale prices, both retailers simultaneously decide their optimal retail prices in the product market. Mathematically, the retailers' problems are given by

$$\begin{cases}\max\limits_{p_1}\Pi_{R,1}^{DD}\left(p_1,p_2\right)=\left(p_1-w_1\right)q_1\left(p_1,p_2\right) \\ \max\limits_{p_2}\Pi_{R,2}^{DD}\left(p_1,p_2\right)=\left(p_2-w_2\right)q_2\left(p_1,p_2\right)\end{cases}, \tag{26}$$

where the subscripts "*R,1*" and "*R,2*" denote retailer 1 and retailer 2, respectively. Solving the FOCs from Eq. (26) yields

$$p_i^{DD}\left(w_i,w_j\right)=\frac{\left(1-\theta\right)\left(2+\theta\right)\alpha+2w_i+\theta w_j}{4-\theta^2},\ i,j=1,2;i\neq j. \tag{27}$$

Expecting the retailers' responses in Eq. (27), the manufacturers independently set their wholesale prices to maximize their profits

$$\max_{w_i}\Pi_{M,i}^{DD}\left(w_i,w_j\right)=\left(w_i-t\right)q_i\left(p_i^{DD}\left(w_i,w_j\right),p_j^{DD}\left(w_i,w_j\right)\right),\ i,j=1,2;i\neq j. \tag{28}$$

Solving Eq. (28), we obtain the manufacturers' optimal wholesale prices as:

$$w_1^{DD}(t) = w_2^{DD}(t) = \frac{(1-\theta)(2+\theta)\alpha + (2-\theta^2)t}{4-\theta-2\theta^2}. \tag{29}$$

Knowing Eq. (27) and Eq. (29), the government sets the optimal tax rate to maximize social welfare in Eq. (15), resulting in

$$t^{DD} = \begin{cases} \dfrac{(2-\theta^2)d - \beta(1-\theta^2)(3-\theta^2)}{(2-\theta^2)\left[2d+\beta(1+\theta)\right]} 2\alpha, \text{ if } d > d^{DD} \\ 0, \text{ otherwise} \end{cases}, \tag{30}$$

where d^{DD} is the tax-free polluting threshold under channel structure *DD* and is obtained as

$$d^{DD} = \frac{(1-\theta^2)(3-\theta^2)}{2-\theta^2}\beta \tag{31}$$

Based on Eq. (30), all other solutions are obtained and summarized in Table 11 in Appendix.

Next, we graphically examine how the environment tax evolves with the environmental damage parameter *d* under different channel structures. By setting $\alpha = 1$, $\beta = 0.5$ and $\theta = 0.5$, Fig. 5 below clearly demonstrates that the government starts imposing environmental taxes at different damage levels for different channel structures and the more integrated channel structures bear heavier tax burdens. In addition, the tax rate always increases in the degree of environmental damage, corresponding to a more stringent tax policy on the manufacturers if their production is more polluting.

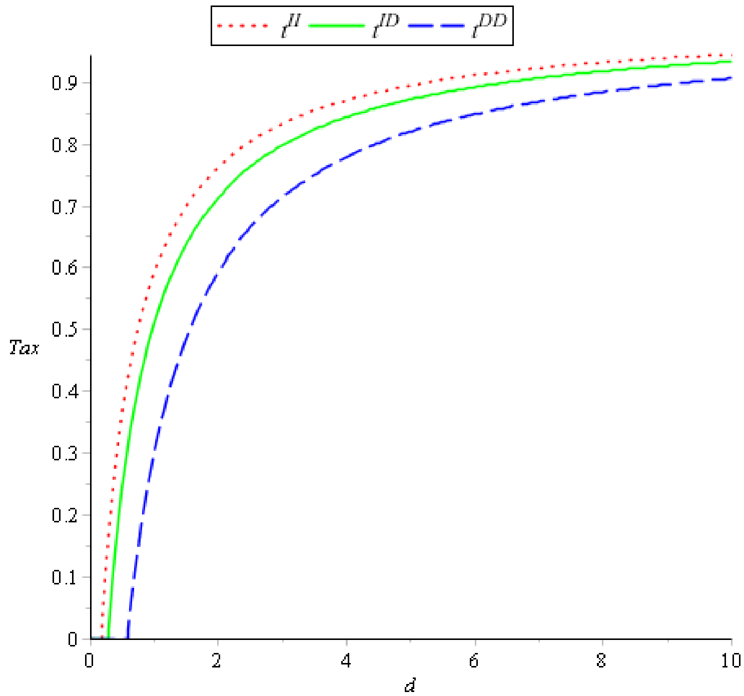


Figure 5. Evolution of the tax rate with respect to the degree of environmental damage

Analytically, comparing the three tax-free polluting thresholds given by Eq. (19), Eq. (25) and Eq. (31), we have $d^{II} < d^{ID} < d^{DD}$ for any $\theta \in [0,1)$. Then, by examining Eq. (18), Eq. (24) and Eq. (30) regarding the tax rate, we have the following results.

Proposition 9. The government's optimal tax policy with two competing supply chains satisfies

(a). If $d \le d^{II}$, then $t^{II} = t^{ID} = t^{DD} = 0$.

(b). If $d^{II} < d \le d^{ID}$, then $t^{II} > t^{ID} = t^{DD} = 0$.

(c). If $d^{ID} < d \le d^{DD}$, then $t^{II} > t^{ID} > t^{DD} = 0$.

(d). If $d > d^{DD}$, then $t^{II} > t^{ID} > t^{DD} > 0$.

Proof. See Appendix.

In resonance with the visual display in Fig. 5, Proposition 9 confirms that, under endogenous environmental taxation, when the channel structure becomes more decentralized (from *II* to *ID* to *DD*), the environmental tax becomes less stringent (the tax-free polluting threshold becomes higher, and the tax rate becomes lower). The reason is the same as that of Proposition 1: a more decentralized channel structure tends to produce less due to double marginalization, and thereby is less polluting.

After discussing the aforementioned channel structures and the government's tax policies, we proceed to analyze the manufacturers' equilibrium channel strategies. We first present the classic result of McGuire and Staelin (1983) under no environmental tax as a benchmark.

Benchmark Theorem (McGuire and Staelin, 1983). Under no environmental tax, with two competing supply chains, channel structure *II* is the unique equilibrium channel structure if $\theta < 0.931$, and channel structures *DD* and *II* are both equilibria if $\theta \geq 0.931$.

The benchmark theorem states that, when there is no environmental tax, channel structure *II* is always an equilibrium, and channel structure *DD* arises as an additional equilibrium only if the products are highly substitutable. This result reveals a benefit of decentralization as the independent retailers help to mitigate competition between manufacturers, thereby enhancing their profits, which is the so-called "retailer buffer" effect (Wang et al., 2011). With highly substitutable products, this retailer buffer effect outweighs double marginalization. In this case, the competition is so intense that *DD* arises as an equilibrium.

Under endogenous environmental taxation in this paper, besides the aforesaid retailer buffer effect, the decentralized channel structure also has the tax saving effect as shown in Proposition 3. Therefore, the condition for *DD* to be an equilibrium under endogenous environmental taxation is more general compared to the benchmark theorem. Define d_1 as

$$d_1 = \frac{\beta(1+\theta)\left[\begin{array}{l}-(2+\theta)(2-\theta^2)(20+4\theta-19\theta^2-\theta^3+4\theta^4)\\+(4+\theta-2\theta^2)(4-\theta-2\theta^2)(6+\theta-3\theta^2)\sqrt{(2-\theta^2)(4-\theta^2)}\end{array}\right]}{(4+2\theta-2\theta^2-\theta^3)(6+\theta-3\theta^2)^2}.$$

We then have the following proposition:

Proposition 10. Under endogenous environmental taxation with two competing supply chains, *II* is the unique equilibrium channel structure if and only if $\theta < 0.931$ and $d < d_1$, otherwise *DD* and *II* are both equilibria, where d_1 satisfies $d^{ID} < d_1 < d^{DD}$ for $\theta < 0.931$, $d_1 = d^{ID}$ for $\theta = 0.931$, and $d_1 < d^{ID}$ for $\theta > 0.931$.

Proof. *II* is an equilibrium channel structure if and only if $\Pi_{M2}^{II} \geq \Pi_{M2}^{ID}$. That is, $\Pi_{M2}^{II} \geq \Pi_{M2}^{ID}$ means that, given that manufacturer 1 chooses integration, manufacturer 2 has no incentive to choose decentralization. By symmetry between the two manufacturers, this means that no one has the incentive to change if the channel structure is *II*, and thus *II* is an equilibrium. Similarly, *DD* is an equilibrium channel structure if and only if $\Pi_{M1}^{DD} \geq \Pi_{M1}^{ID}$. Therefore, it suffices to prove that $\Pi_{M2}^{II} > \Pi_{M2}^{ID}$ holds (*II* is an equilibrium) for any θ and d, and $\Pi_{M1}^{DD} < \Pi_{M1}^{ID}$ holds (*DD* is not an equilibrium) if and only if $\theta < 0.931$ and $d < d_1$. The remainder of the proof consists of basic calculations and is moved to the Appendix.

Figure 6 graphically depicts Proposition 10, with 1.330β and 0.107β being the values of d_1 at $\theta = 0$ and $\theta = 0.931$, respectively. From Figure 6 and Proposition 10, we can see that, when $d \leq 0.107\beta$, the result under endogenous environmental taxation is the same as the benchmark theorem. That is, when $d \leq 0.107\beta$, the critical θ value above which *DD* is an equilibrium is $\theta = 0.931$, the same as in the benchmark theorem. This means that, when the technology is low-polluting, the tax saving effect of decentralization does not make a difference, and the condition for *DD* to be an equilibrium is the same as in the no-tax case.

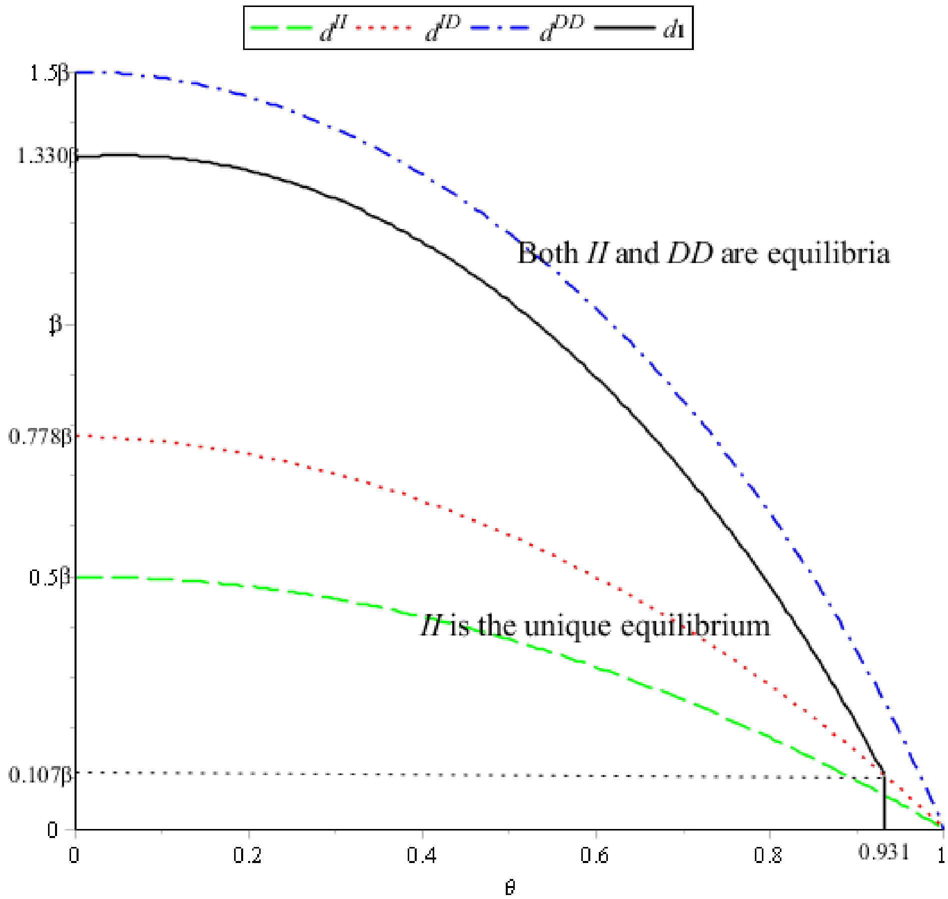


Figure 6. Equilibrium channel strategies with two competing supply chains

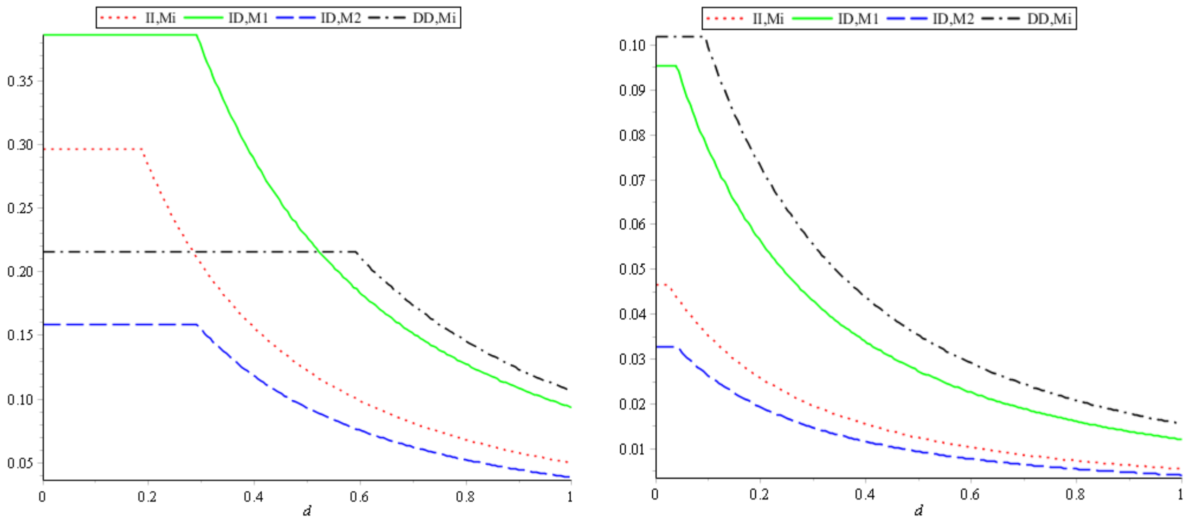
It can be seen from Figure 6 and Proposition 10 that the tax saving effect of decentralization makes a difference when the technology is more polluting than a small threshold ($d > 0.107\beta$). Specifically, when d increases from 0.107β to 1.330β, the critical θ value above which *DD* is an equilibrium decreases from 0.931 to 0, and when $d \geq 1.330\beta$, *DD* is always an equilibrium regardless of θ. The implications are that, as the technology becomes more polluting, the requirement on product substitutability becomes lower for *DD* to be an equilibrium, and when the technology is highly polluting, *DD* is always an equilibrium regardless of product substitutability.

Figure 6 and Proposition 10 can also be interpreted from the perspective of product substitutability. That is, when θ increases from 0 to 0.931, the critical d value above which *DD* is an equilibrium decreases from 1.330β to 0.107β, and when $\theta \geq 0.931$, *DD* is always an equilibrium regardless of d. In other words, as the products become more substitutable, the requirement on technology polluting level becomes lower for *DD* to be an equilibrium. Especially, when the products are highly substitutable, *DD* is always an equilibrium regardless of how polluting the technology is.

One technical detail about Proposition 10 worth mentioning is that, it is not a coincidence that $d_1 = d^{ID}$ at $\theta = 0.931$. To see this, denoting d_1 and d^{ID} by $d_1(\theta)$ and $d^{ID}(\theta)$ to highlight that their values change with θ. From the proof of Proposition 10 in the Appendix, $d_1(\theta)$ represents a combination of θ and d such that, when channel structure *ID* is taxed and *DD* is not taxed, a firm is indifferent between decentralization and integration given that its competitor is decentralized. That is, it holds $\Pi_{M,1}^{DD} = \Pi_{M,1}^{ID}$ at any point $(\theta, d_1(\theta))$ within the range $d^{ID} < d \leq d^{DD}$. On the other hand, $\theta = 0.931$ is the value such that a firm is indifferent between decentralization and integration given that its competitor is decentralized when there is no environmental tax (McGuire and Staelin, 1983). That is, it holds $\Pi_{M,1}^{DD} = \Pi_{M,1}^{ID}$ at $\theta = 0.931$ when $t^{ID} = t^{DD} = 0$. Recall that $t^{ID} = t^{DD} = 0$ when $d = d^{ID}$, we readily have $\Pi_{M,1}^{DD} = \Pi_{M,1}^{ID}$ at the point $(0.931, d^{ID}(0.931))$. Therefore, $d_1(0.931) = d^{ID}(0.931)$ simply reflects that the indifference condition $\Pi_{M,1}^{DD} = \Pi_{M,1}^{ID}$ is continuous in d at $d = d^{ID}$. The essential reason is that the tax rate t^{ID} given by Eq. (24) is continuous in d at $d = d^{ID}$.

In summary, Proposition 10 suggests that, under endogenous environmental taxation, manufacturers are more likely to decentralize in equilibrium when their technologies are more polluting. Similar to the result of McGuire and Staelin (1983) under no environmental tax, it can be verified that, whenever channel structure *DD* and *II* are both equilibria, *DD* is dominant in that the manufacturers' profits are higher. Furthermore, similar to the single supply chain case, comparing Tables 9 and 11 in the Appendix shows that, for $d > d^{DD}$, the retail price and quantity, and social welfare are all the same and at the first-best level under *DD* and *II*. This leads to the same two important implications as in the single supply chain case. First, manufacturers' higher profits under decentralization stem from the tax cut for less polluting industry structures, which does not affect social welfare or consumer surplus as long as their technologies are polluting enough that the focal issue remains the environmental damage caused by excessive production rather than the economic efficiency loss caused by firms' market power. Second, when the manufacturers decentralize, the government could achieve the first-best social welfare with a lower tax rate, a higher industry profit, and the same consumer surplus, and thus may gain higher public support for its environmental tax policy. The second point also implies that, from a prescriptive perspective, the government has the incentive to be a follower and set its tax policy to induce manufactures to decentralize, thereby achieving higher industry profit without hurting any stakeholder.

Next, by setting $\alpha = 1$ and $\beta = 0.5$, Fig. 7 graphically demonstrates how the manufacturers' profits vary with the environmental damage parameter d for (a) $\theta = 0.5$ and (b) $\theta = 0.95$ under different channel structures. Fig. 7(a) indicates that, for $\theta = 0.5 < 0.931$, *II* is the unique equilibrium when $d < 0.5224$ and *DD* arises as another dominant equilibrium when $d \geq 0.5224$ (when the profit line for *ID-M1* crosses below that for *DD*). On the other hand, Fig. 7(b) confirms that, for highly substitutable products when $\theta = 0.95 > 0.931$, both *II* and *DD* are equilibrium channel structures with *DD* being the dominant equilibrium regardless of the environmental damage level *d*. In addition, Fig. 7 clearly shows that manufacturers' profits always decrease in *d* once it is high enough to trigger the environmental tax. This means that the manufacturers are incentivized to improve their production technology in order to boost up their profitability.



(a) $\theta = 0.5$ (b) $\theta = 0.95$

Figure 7. Manufacturers' profits under different channel structures with respect to *d*

Similarly, letting $\alpha = 1$, $\beta = 0.5$, and $\theta = 0.5$, we plot social welfare under different channel structures as functions of the environmental damage parameter *d* as shown in Fig. 8. It clearly shows that the traditional ranking of social welfare $SW^{II} > SW^{ID} > SW^{DD}$ holds when the environmental damage level *d* is relatively low. On the other hand, when environmental damage is high enough that $d > d^{DD}$, social welfare achieves the first-best level under the two equilibrium channel structures *DD* and *II* (the two social welfare curves coincide) and is higher than that under the asymmetric channel structures *ID* and *DI*.

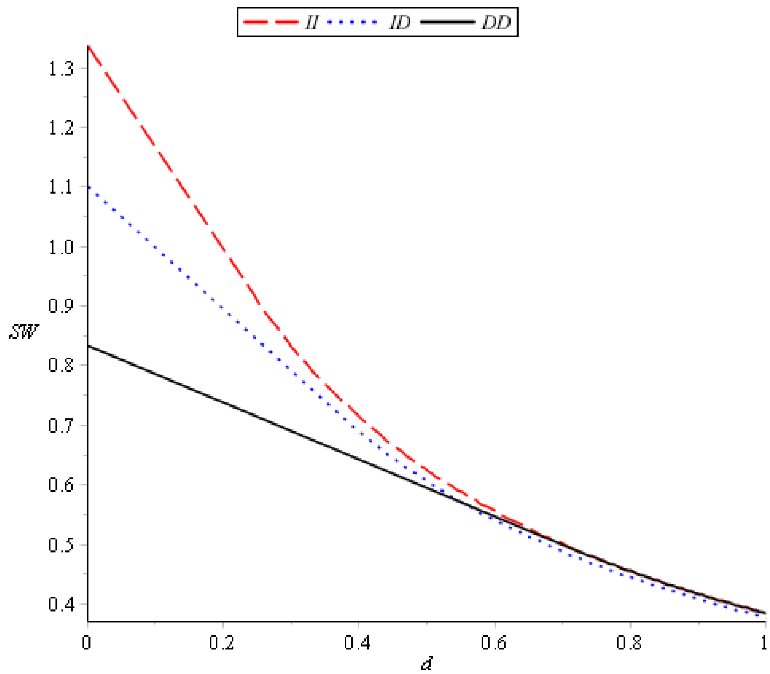


Figure 8. Social welfare under different channel structures

5.4. Discussions on extensions with two competing supply chains

To further examine the robustness of our analytical results for two competing supply chains, we also consider the same extensions with a single supply chain presented in Section 4. Given that no additional insights are obtained beyond what we have garnered here, the details are omitted and only a summary of the results is reported below for the sake of space.

For the linear environmental damage extension, we are able to derive analytical results on the equilibrium channel structure, which is structurally the same as what is presented in Figure 6 except for shifted d thresholds on the vertical axis and the dividing curve for the two zones with only II or both DD and II as the equilibrium channel structure.

For the extensions with operational efficiency and transport emission, numerical experiments confirm that the main results in Proposition 10 can be qualitatively carried over. On the other hand, when subsidies are allowed, both DD and II will always arise as equilibrium channel structures.

For the cases with quadratic taxes and environmentally-friendly manufacturers, the complex functional forms prevent us from deriving any definite results on equilibrium channel structures.

In summary, the main results on equilibrium channel structures for two competing supply chains can be extended to the majority of the aforesaid extensions, confirming the robustness of our analytical results.

6. Conclusions

This paper presents a simple model to examine distribution channel strategies under environmental taxation. The main findings are summarized as follows. The environmental tax becomes less stringent when the distribution channel structure becomes more decentralized. The reason is that a more decentralized channel structure tends to produce less due to double marginalization, and thereby is less polluting. This has important implications on manufacturers' channel strategies. First, contrary to the classic double marginalization problem, a monopolistic manufacturer can benefit from decentralization when its technology is sufficiently polluting. Second, with two competing manufacturers, both are more likely to decentralize in equilibrium when their technologies are more environmentally damaging. Moreover, manufacturers' higher profits under decentralization stem from the tax cut for less polluting industry structures, which does not affect the social welfare or consumer surplus as long as their technologies are polluting enough that environmental protection remains the focal issue. Furthermore, the robustness of the analytical results is investigated by extending the base models to a variety of scenarios with linear environmental damage, integration efficiency, transport emission, quadratic taxation, an environmentally-friendly manufacturer as well as by allowing subsidies for low polluting technology.

Our results suggest that, for heavily polluting industries, when the industry structure becomes more decentralized, the government can achieve its environmental protection goal with a lower tax rate and higher industry profit, thereby garnering more public support for its environmental tax policy. Therefore, from a prescriptive viewpoint, the government has the incentive to set its tax policy conditional on manufacturers' channel choice, thereby inducing heavy polluters to decentralize.

Several possible directions can be explored in future research. For instance, it is worthwhile to examine channel strategies and environmental taxation in a market with uncertainty and information asymmetry to relax the current perfect information assumption. In addition, this research considers only exclusive decentralized or integrated channel structure, but multi-channel and omni-channel strategies have been observed in real-world businesses, it will be worthwhile to consider how manufacturers' channel selection changes with more complex channel structures. Still another worthy topic is to add environmental awareness and incorporate uncertainty into the demand function and examine further how it may affect manufacturers' channel decision.

Appendix.

Table 3. Solutions in a single supply chain

	Integrated channel		Decentralized channel	
	$d \le \beta$	$d > \beta$	$d \le 3\beta$	$d > 3\beta$
Tax rate (t)	0	$\frac{(d-\beta)\alpha}{\beta+d}$	0	$\frac{(d-3\beta)\alpha}{\beta+d}$
Wholesale price (w)	N/A	N/A	$\frac{\alpha}{2}$	$\frac{(d-\beta)\alpha}{\beta+d}$

Quantity (q)	$\frac{\alpha}{2\beta}$	$\frac{\alpha}{\beta+d}$	$\frac{\alpha}{4\beta}$	$\frac{\alpha}{\beta+d}$
Retail price (p)	$\frac{\alpha}{2}$	$\frac{d\alpha}{\beta+d}$	$\frac{3\alpha}{4}$	$\frac{d\alpha}{\beta+d}$
Manufacturer's profit (Π_M)	$\frac{\alpha^2}{4\beta}$	$\frac{\beta\alpha^2}{(\beta+d)^2}$	$\frac{\alpha^2}{8\beta}$	$\frac{2\beta\alpha^2}{(\beta+d)^2}$
Retailer's profit (Π_R)	N/A	N/A	$\frac{\alpha^2}{16\beta}$	$\frac{\beta\alpha^2}{(\beta+d)^2}$
Channel profit ($\Pi_M+\Pi_R$)	$\frac{\alpha^2}{4\beta}$	$\frac{\beta\alpha^2}{(\beta+d)^2}$	$\frac{3\alpha^2}{16\beta}$	$\frac{3\beta\alpha^2}{(\beta+d)^2}$
Consumer surplus (CS)	$\frac{\alpha^2}{8\beta}$	$\frac{\beta\alpha^2}{2(\beta+d)^2}$	$\frac{\alpha^2}{32\beta}$	$\frac{\beta\alpha^2}{2(\beta+d)^2}$
Social welfare (SW)	$\frac{(3\beta-d)\alpha^2}{8\beta^2}$	$\frac{\alpha^2}{2(\beta+d)}$	$\frac{(7\beta-d)\alpha^2}{32\beta^2}$	$\frac{\alpha^2}{2(\beta+d)}$

Table 4. Solutions in a single supply chain with linear environmental damage

	Integrated channel		Decentralized channel	
	$d \le \frac{\alpha}{2}$	$d > \frac{\alpha}{2}$	$d \le \frac{3\alpha}{4}$	$d > \frac{3\alpha}{4}$
Tax rate (t)	0	$2d-\alpha$	0	$4d-3\alpha$
Wholesale price (w)	N/A	N/A	$\frac{\alpha}{2}$	$2d-\alpha$
Quantity (q)	$\frac{\alpha}{2\beta}$	$\frac{\alpha-d}{\beta}$	$\frac{\alpha}{4\beta}$	$\frac{\alpha-d}{\beta}$

Retail price (p)	$\frac{\alpha}{2}$	d	$\frac{3\alpha}{4}$	d
Manufacturer's profit (Π_M)	$\frac{\alpha^2}{4\beta}$	$\frac{(\alpha-d)^2}{\beta}$	$\frac{\alpha^2}{8\beta}$	$\frac{2(\alpha-d)^2}{\beta}$
Retailer's profit (Π_R)	N/A	N/A	$\frac{\alpha^2}{16\beta}$	$\frac{(\alpha-d)^2}{\beta}$
Channel profit ($\Pi_M+\Pi_R$)	$\frac{\alpha^2}{4\beta}$	$\frac{(\alpha-d)^2}{\beta}$	$\frac{3\alpha^2}{16\beta}$	$\frac{3(\alpha-d)^2}{\beta}$
Consumer surplus (CS)	$\frac{\alpha^2}{8\beta}$	$\frac{(\alpha-d)^2}{2\beta}$	$\frac{\alpha^2}{32\beta}$	$\frac{(\alpha-d)^2}{2\beta}$
Social welfare (SW)	$\frac{(3\alpha-4d)\alpha}{8\beta}$	$\frac{(\alpha-d)^2}{2\beta}$	$\frac{(7\alpha-8d)\alpha}{32\beta}$	$\frac{(\alpha-d)^2}{2\beta}$

Table 5. Solutions in a single supply chain with operation efficiency under integration

	Integrated channel		Decentralized channel	
	$d\le\frac{\beta}{\eta}$	$d>\frac{\beta}{\eta}$	$d\le 3\beta$	$d>3\beta$
Tax rate (t)	0	$\frac{(\eta d-\beta)\alpha}{\eta d+\beta}$	0	$\frac{(d-3\beta)\alpha}{\beta+d}$
Wholesale price (w)	N/A	N/A	$\frac{\alpha}{2}$	$\frac{(d-\beta)\alpha}{\beta+d}$
Quantity (q)	$\frac{\alpha}{2\beta}$	$\frac{\alpha}{\eta d+\beta}$	$\frac{\alpha}{4\beta}$	$\frac{\alpha}{\beta+d}$

Retail price (p)	$\frac{\alpha}{2}$	$\frac{\eta d\alpha}{\eta d+\beta}$	$\frac{3\alpha}{4}$	$\frac{d\alpha}{\beta+d}$
Manufacturer's profit (Π_M)	$\frac{\alpha^2}{4\beta}$	$\frac{\beta\alpha^2}{(\eta d+\beta)^2}$	$\frac{\alpha^2}{8\beta}$	$\frac{2\beta\alpha^2}{(\beta+d)^2}$
Retailer's profit (Π_R)	N/A	N/A	$\frac{\alpha^2}{16\beta}$	$\frac{\beta\alpha^2}{(\beta+d)^2}$
Channel profit ($\Pi_M+\Pi_R$)	$\frac{\alpha^2}{4\beta}$	$\frac{\beta\alpha^2}{(\eta d+\beta)^2}$	$\frac{3\alpha^2}{16\beta}$	$\frac{3\beta\alpha^2}{(\beta+d)^2}$
Consumer surplus (CS)	$\frac{\alpha^2}{8\beta}$	$\frac{\beta\alpha^2}{2(\eta d+\beta)^2}$	$\frac{\alpha^2}{32\beta}$	$\frac{\beta\alpha^2}{2(\beta+d)^2}$
Social welfare (SW)	$\frac{(3\beta-\eta d)\alpha^2}{8\beta^2}$	$\frac{\alpha^2}{2(\eta d+\beta)}$	$\frac{(5\beta-d)\alpha^2}{32\beta^2}$	$\frac{\alpha^2}{2(\beta+d)}$

Table 6. Solutions in a single supply chain with transport emission

	Integrated channel		Decentralized channel	
	$d\le\beta-\eta^T d^T$	$d>\beta-\eta^T d^T$	$d\le 3\beta-d^T$	$d>3\beta-d^T$
Tax rate (t)	0	$\frac{(\eta^T d^T+d-\beta)\alpha}{\eta^T d^T+\beta+d}$	0	$\frac{(d^T+d-3\beta)\alpha}{d^T+d+\beta}$
Wholesale price (w)	N/A	N/A	$\frac{\alpha}{2}$	$\frac{(d^T+d-\beta)\alpha}{d^T+d+\beta}$
Quantity (q)	$\frac{\alpha}{2\beta}$	$\frac{\alpha}{\eta^T d^T+\beta+d}$	$\frac{\alpha}{4\beta}$	$\frac{\alpha}{d^T+d+\beta}$

Retail price (p)	$\frac{\alpha}{2}$	$\frac{\left(\eta^T d^T + d\right)\alpha}{\eta^T d^T + \beta + d}$	$\frac{3\alpha}{4}$	$\frac{\left(d^T + d\right)\alpha}{d^T + d + \beta}$
Manufacturer's profit (Π_M)	$\frac{\alpha^2}{4\beta}$	$\frac{\beta\alpha^2}{\left(\eta^T d^T + \beta + d\right)^2}$	$\frac{\alpha^2}{8\beta}$	$\frac{2\beta\alpha^2}{\left(d^T + d + \beta\right)^2}$
Retailer's profit (Π_R)	N/A	N/A	$\frac{\alpha^2}{16\beta}$	$\frac{\beta\alpha^2}{\left(d^T + d + \beta\right)^2}$
Channel profit ($\Pi_M + \Pi_R$)	$\frac{\alpha^2}{4\beta}$	$\frac{\beta\alpha^2}{\left(\eta^T d^T + \beta + d\right)^2}$	$\frac{3\alpha^2}{16\beta}$	$\frac{3\beta\alpha^2}{\left(d^T + d + \beta\right)^2}$
Consumer surplus (CS)	$\frac{\alpha^2}{8\beta}$	$\frac{\beta\alpha^2}{2\left(\eta^T d^T + \beta + d\right)^2}$	$\frac{\alpha^2}{32\beta}$	$\frac{\beta\alpha^2}{2\left(d^T + d + \beta\right)^2}$
Social welfare (SW)	$\frac{\left(3\beta - \eta^T d^T - d\right)\alpha^2}{8\beta^2}$	$\frac{\alpha^2}{2\left(\eta^T d^T + \beta + d\right)}$	$\frac{\left(5\beta - d^T - d\right)\alpha^2}{32\beta^2}$	$\frac{\alpha^2}{2\left(d^T + d + \beta\right)}$

Table 7. Solutions in a single supply chain with a quadratic tax

	Integrated channel		Decentralized channel	
	$d \le \beta$	$d > \beta$	$d \le 3\beta$	$d > 3\beta$
Tax rate (t)	0	$d - \beta$	0	$d - 3\beta$
Wholesale price (w)	N/A	N/A	$\frac{\alpha}{2}$	$\frac{\left(d - \beta\right)\alpha}{d + \beta}$
Quantity (q)	$\frac{\alpha}{2\beta}$	$\frac{\alpha}{d + \beta}$	$\frac{\alpha}{4\beta}$	$\frac{\alpha}{d + \beta}$
Retail price (p)	$\frac{\alpha}{2}$	$\frac{d\alpha}{d + \beta}$	$\frac{3\alpha}{4}$	$\frac{d\alpha}{d + \beta}$

Manufacturer's profit (Π_M)	$\frac{\alpha^2}{4\beta}$	$\frac{\alpha^2}{2(d+\beta)}$	$\frac{\alpha^2}{8\beta}$	$\frac{\alpha^2}{2(d+\beta)}$
Retailer's profit (Π_R)	N/A	N/A	$\frac{\alpha^2}{16\beta}$	$\frac{\beta\alpha^2}{(d+\beta)^2}$
Channel profit ($\Pi_M+\Pi_R$)	$\frac{\alpha^2}{4\beta}$	$\frac{\alpha^2}{2(d+\beta)}$	$\frac{3\alpha^2}{16\beta}$	$\frac{3\beta\alpha^2}{(d+3\beta)^2}$
Consumer surplus (CS)	$\frac{\alpha^2}{8\beta}$	$\frac{\beta\alpha^2}{2(d+\beta)^2}$	$\frac{\alpha^2}{32\beta}$	$\frac{\beta\alpha^2}{2(d+\beta)^2}$
Social welfare (SW)	$\frac{(3\beta-d)\alpha^2}{8\beta^2}$	$\frac{\alpha^2}{2(d+\beta)}$	$\frac{(7\beta-d)\alpha^2}{32\beta^2}$	$\frac{\alpha^2}{2(d+\beta)}$

Table 8. Solutions in a single supply chain with an environmentally-friendly manufacturer

	Integrated channel		Decentralized channel	
	$d\le\beta$	$d>\beta$	$d\le 3\beta$	$d>3\beta$
Tax rate (t)	0	$\frac{(d-\beta)\alpha}{\beta+d+d\mu}$	0	$\frac{(d-3\beta)\alpha}{\beta+d+d\mu}$
Wholesale price (w)	N/A	N/A	$\frac{(2\beta+d\mu)\alpha}{4\beta+d\mu}$	$\frac{(d+d\mu-\beta)\alpha}{\beta+d+d\mu}$
Quantity (q)	$\frac{\alpha}{2\beta+d\mu}$	$\frac{\alpha}{\beta+d+d\mu}$	$\frac{\alpha}{4\beta+d\mu}$	$\frac{\alpha}{\beta+d+d\mu}$
Retail price (p)	$\frac{(\beta+d\mu)\alpha}{2\beta+d\mu}$	$\frac{(1+\mu)d\alpha}{\beta+d+d\mu}$	$\frac{(3\beta+d\mu)\alpha}{4\beta+d\mu}$	$\frac{(1+\mu)\alpha}{\beta+d+d\mu}$

Manufacturer's profit (Π_M)	$\frac{\alpha^2}{2(2\beta+d\mu)}$	$\frac{(2\beta+\mu d)\alpha^2}{2(\beta+d+d\mu)^2}$	$\frac{\alpha^2}{2(4\beta+d\mu)}$	$\frac{(4\beta+\mu d)\alpha^2}{2(\beta+d+d\mu)^2}$
Retailer's profit (Π_R)	N/A	N/A	$\frac{\beta\alpha^2}{(4\beta+d\mu)^2}$	$\frac{\beta\alpha^2}{2(\beta+d+d\mu)^2}$
Channel profit ($\Pi_M+\Pi_R$)	$\frac{\alpha^2}{2(2\beta+d\mu)}$	$\frac{(2\beta+\mu d)\alpha^2}{2(\beta+d+d\mu)^2}$	$\frac{(6\beta+d\mu)\alpha^2}{2(4\beta+d\mu)^2}$	$\frac{(6\beta+\mu d)\alpha^2}{2(\beta+d+d\mu)^2}$
Consumer surplus (CS)	$\frac{\beta\alpha^2}{2(2\beta+d\mu)^2}$	$\frac{\beta\alpha^2}{2(\beta+d+d\mu)^2}$	$\frac{\beta\alpha^2}{2(4\beta+d\mu)^2}$	$\frac{\beta\alpha^2}{2(\beta+d+d\mu)^2}$
Social welfare (SW)	$\frac{(3\beta-d+d\mu)\alpha^2}{2(2\beta+d\mu)^2}$	$\frac{\alpha^2}{2(\beta+d+d\mu)}$	$\frac{(7\beta+d\mu-d)\alpha^2}{2(4\beta+d\mu)^2}$	$\frac{\alpha^2}{2(\beta+d+d\mu)}$

Table 9. Solutions under channel structure *II* ($i=1,2$)

	Channel structure *II*	
	$d \le d^{II}$	$d > d^{II}$
Tax rate (t^{II})	0	$\frac{\left[2d-\beta\left(1-\theta^2\right)\right]\alpha}{2d+\beta(1+\theta)}$
Quantity (q_i^{II})	$\frac{\alpha}{\beta(1+\theta)(2-\theta)}$	$\frac{\alpha}{2d+\beta(1+\theta)}$
Retail price (p_i^{II})	$\frac{(1-\theta)\alpha}{2-\theta}$	$\frac{2d\alpha}{2d+\beta(1+\theta)}$
Manufacturers' profit ($\Pi_{M,i}^{II}$)	$\frac{(1-\theta)\alpha^2}{\beta(1+\theta)(2-\theta)^2}$	$\frac{\beta\left(1-\theta^2\right)\alpha^2}{\left[2d+\beta(1+\theta)\right]^2}$

Consumer surplus (CS^{II})	$\frac{\alpha^2}{\beta(1+\theta)(2-\theta)^2}$	$\frac{\beta(1+\theta)\alpha^2}{\left[2d+\beta(1+\theta)\right]^2}$
Social welfare (SW^{II})	$\frac{\left(3\beta+\beta\theta-2\beta\theta^2-2d\right)\alpha^2}{\beta^2(1+\theta)^2(2-\theta)^2}$	$\frac{\alpha^2}{2d+\beta(1+\theta)}$

Table 10. Solutions under channel structure *ID*

	Channel structure *ID*	
	$d \le d^{ID}$	$d > d^{ID}$
Tax rate (t^{ID})	0	$\frac{B\alpha}{X}$
Wholesale price (w^{ID})	$\frac{(1-\theta)(2+\theta)\alpha}{2\left(2-\theta^2\right)}$	$\frac{C\alpha}{X}$
Product 1's quantity (q_1^{ID})	$\frac{\left(4+\theta-2\theta^2\right)\alpha}{2\beta(1+\theta)(2-\theta)\left(2-\theta^2\right)}$	$\frac{\left(4+\theta-2\theta^2\right)\left(6+\theta-3\theta^2\right)\alpha}{X}$
Product 2's quantity (q_2^{ID})	$\frac{\alpha}{2\beta(1+\theta)(2-\theta)}$	$\frac{\left(2-\theta^2\right)\left(6+\theta-3\theta^2\right)\alpha}{X}$
Product 1's retail price (p_1^{ID})	$\frac{(1-\theta)\left(4+\theta-2\theta^2\right)\alpha}{2(2-\theta)\left(2-\theta^2\right)}$	$\frac{D\alpha}{X}$
Product 2's retail price (p_2^{ID})	$\frac{(1-\theta)\left(3-\theta^2\right)\alpha}{(2-\theta)\left(2-\theta^2\right)}$	$\frac{E\alpha}{X}$
Manufacturer 1's profit ($\Pi_{M,1}^{ID}$)	$\frac{(1-\theta)\left(4+\theta-2\theta^2\right)^2\alpha^2}{4\beta(1+\theta)(2-\theta)^2\left(2-\theta^2\right)^2}$	$\frac{F\alpha^2}{X^2}$

Manufacturer 2's profit ($\Pi_{M,2}^{ID}$)	$\dfrac{(1-\theta)(2+\theta)\alpha^2}{4\beta(1+\theta)(2-\theta)(2-\theta^2)}$	$\dfrac{G\alpha^2}{X^2}$
Retailer 2's profit ($\Pi_{R,2}^{ID}$)	$\dfrac{(1-\theta)\alpha^2}{4\beta(1+\theta)(2-\theta)^2}$	$\dfrac{H\alpha^2}{X^2}$
Channel 1's profit ($=\Pi_{M,1}^{ID}$)	$\dfrac{(1-\theta)(4+\theta-2\theta^2)^2\alpha^2}{4\beta(1+\theta)(2-\theta)^2(2-\theta^2)^2}$	$\dfrac{F\alpha^2}{X^2}$
Channel 2's profit ($=\Pi_{M,2}^{ID}+\Pi_{R,2}^{ID}$)	$\dfrac{(1-\theta)(3-\theta^2)\alpha^2}{2\beta(1+\theta)(2-\theta)^2(2-\theta^2)}$	$\dfrac{I\alpha^2}{X^2}$
Consumer surplus (CS^{ID})	$\dfrac{(20+4\theta-19\theta^2-\theta^3+4\theta^4)\alpha^2}{8\beta(1+\theta)(2-\theta)^2(2-\theta^2)^2}$	$\dfrac{J\alpha^2}{2X^2}$
Social welfare (SW^{ID})	$\dfrac{A\alpha^2}{8\beta^2(1+\theta)^2(2-\theta)^2(2-\theta^2)^2}$	$\dfrac{(6+\theta-3\theta^2)^2\alpha^2}{2X}$

where

$A=\beta(1+\theta)(76-36\theta-85\theta^2+41\theta^3+24\theta^4-12\theta^5)-(6+\theta-3\theta^2)^2 d$.

$B=(6+\theta-3\theta^2)^2 d-\beta(1-\theta^2)(28+8\theta-25\theta^2-4\theta^3+6\theta^4)$.

$C=(6+\theta-3\theta^2)^2 d+\beta(1-\theta^2)(4-3\theta^2)(1+\theta-\theta^2)$.

$D=(6+\theta-3\theta^2)^2 d-\beta(1-\theta^2)(2-\theta)(2-\theta^2)$.

$E=(6+\theta-3\theta^2)^2 d+\beta(1-\theta^2)(2-\theta)(4+\theta-2\theta^2)$.

$F=\beta(1-\theta^2)(4+\theta-2\theta^2)^2(6+\theta-3\theta^2)^2$.

$G=\beta(1-\theta^2)(2-\theta^2)(4-\theta^2)(6+\theta-3\theta^2)^2$.

$H=\beta(1-\theta^2)(2-\theta^2)^2(6+\theta-3\theta^2)^2$.

$$I = 2\beta\left(1-\theta^2\right)\left(2-\theta^2\right)\left(3-\theta^2\right)\left(6+\theta-3\theta^2\right)^2.$$

$$J = \beta\left(1+\theta\right)\left(6+\theta-3\theta^2\right)^2\left(20+4\theta-19\theta^2-\theta^3+4\theta^4\right).$$

$$X = \left(6+\theta-3\theta^2\right)^2 d + \beta\left(1+\theta\right)\left(20+4\theta-19\theta^2-\theta^3+4\theta^4\right).$$

Table 11. Solutions under channel structure *DD* ($i=1,2$)

	Channel structure *DD*	
	$d \le d^{DD}$	$d > d^{DD}$
Tax rate (t^{DD})	0	$\frac{L\alpha}{\left(2-\theta^2\right)\left[2d+\beta\left(1+\theta\right)\right]}$
Wholesale price (w_i^{DD})	$\frac{\left(1-\theta\right)\left(2+\theta\right)\alpha}{4-\theta-2\theta^2}$	$\frac{\left[2d-\beta\left(1-\theta^2\right)\right]\alpha}{2d+\beta\left(1+\theta\right)}$
Quantity (q_i^{DD})	$\frac{\left(2-\theta^2\right)\alpha}{\beta\left(1+\theta\right)\left(2-\theta\right)\left(4-\theta-2\theta^2\right)}$	$\frac{\alpha}{2d+\beta\left(1+\theta\right)}$
Retail price (p_i^{DD})	$\frac{2\left(1-\theta\right)\left(3-\theta^2\right)\alpha}{\left(2-\theta\right)\left(4-\theta-2\theta^2\right)}$	$\frac{2d\alpha}{2d+\beta\left(1+\theta\right)}$
Manufacturers' profit ($\Pi_{M,i}^{DD}$)	$\frac{\left(1-\theta\right)\left(2+\theta\right)\left(2-\theta^2\right)\alpha^2}{\beta\left(1+\theta\right)\left(2-\theta\right)\left(4-\theta-2\theta^2\right)^2}$	$\frac{\beta\left(1-\theta^2\right)\left(4-\theta^2\right)\alpha^2}{\left(2-\theta^2\right)\left[2d+\beta\left(1+\theta\right)\right]^2}$
Retailers' profit ($\Pi_{R,i}^{DD}$)	$\frac{\left(1-\theta\right)\left(2-\theta^2\right)^2\alpha^2}{\beta\left(1+\theta\right)\left(2-\theta\right)^2\left(4-\theta-2\theta^2\right)^2}$	$\frac{\beta\left(1-\theta^2\right)\alpha^2}{\left[2d+\beta\left(1+\theta\right)\right]^2}$
Channel profit ($=\Pi_{M,i}^{DD}+\Pi_{R,i}^{DD}$)	$\frac{2\left(1-\theta\right)\left(2-\theta^2\right)\left(3-\theta^2\right)\alpha^2}{\beta\left(1+\theta\right)\left(2-\theta\right)^2\left(4-\theta-2\theta^2\right)^2}$	$\frac{2\beta\left(1-\theta^2\right)\left(3-\theta^2\right)\alpha^2}{\left(2-\theta^2\right)\left[2d+\beta\left(1+\theta\right)\right]^2}$

Consumer surplus (CS^{DD})	$\dfrac{\left(2-\theta^2\right)^2 \alpha^2}{\beta(1+\theta)(2-\theta)^2\left(4-\theta-2\theta^2\right)^2}$	$\dfrac{\beta(1+\theta)\alpha^2}{\left[2d+\beta(1+\theta)\right]^2}$
Social welfare (SW^{DD})	$\dfrac{K\alpha^2}{\beta^2(1+\theta)^2(2-\theta)^2\left(4-\theta-2\theta^2\right)^2}$	$\dfrac{\alpha^2}{2d+\beta(1+\theta)}$

where

$K=\left(2-\theta^2\right)\left[\beta(1+\theta)\left(14-12\theta-5\theta^2+4\theta^3\right)-\left(4-2\theta^2\right)d\right]$.

$L=2\left[\left(2-\theta^2\right)d-\beta\left(1-\theta^2\right)\left(3-\theta^2\right)\right]$.

Proof of Proposition 2

Part (a) and (c) directly follow from the "Manufacturer's profit" in Table 3. For part (b), we have

$$\Pi_M^D-\Pi_M^I=\frac{\alpha^2}{8\beta}-\frac{\beta\alpha^2}{(\beta+d)^2}=\frac{\left(d^2+2\beta d-7\beta^2\right)\alpha^2}{8\beta(\beta+d)^2}, \text{ for } \beta<d\le 3\beta .$$

Algebraic calculation shows that $\Pi_M^D-\Pi_M^I>0$ if $\left(2\sqrt{2}-1\right)\beta<d\le 3\beta$, and $\Pi_M^D-\Pi_M^I\le 0$ if $\beta<d\le\left(2\sqrt{2}-1\right)\beta$, with equality if and only if $d=\left(2\sqrt{2}-1\right)\beta$.

Proof of Proposition 3

Part (a) and (c) directly follow from the "Manufacturer's profit" in Table 4. For part (b), we have

$$\Pi_M^{DL}-\Pi_M^{IL}=\frac{\alpha^2}{8\beta}-\frac{(\alpha-d)^2}{\beta}=-\frac{7\alpha^2-16\alpha d+8d^2}{8\beta}, \text{ for } \frac{1}{2}\alpha<d\le\frac{3}{4}\alpha .$$

Algebraic calculation shows that $\Pi_M^{DL}-\Pi_M^{IL}>0$ if $\left(1-\frac{\sqrt{2}}{4}\right)\alpha<d\le\frac{3}{4}\alpha$, and $\Pi_M^{DL}-\Pi_M^{IL}\le 0$ otherwise, with equality if and only if $d=\left(1-\frac{\sqrt{2}}{4}\right)\alpha$.

Proof of Proposition 4

Based on Table 5, the whole proof can be divided into two cases: (a). $\eta \le \frac{1}{3}$, and (b). $\eta > \frac{1}{3}$.

(a). $\eta \le \frac{1}{3}$: It can be easily seen that $\Pi_M^{DE} < \Pi_M^{IE}$ always holds.

(b). $\eta > \frac{1}{3}$: $\Pi_M^{DE} < \Pi_M^{IE}$ holds for $\frac{\left(2\sqrt{2}-1\right)\beta}{\eta} < d < 3\beta$. However, when $d > 3\beta$, we have

(i). If $d > 3\beta$ and $\eta \ge \frac{\sqrt{2}}{2}$, then $\Pi_M^{DE} > \Pi_M^{IE}$;

(ii) If $d > 3\beta$ and $\eta < \frac{\sqrt{2}}{2}$, then $\Pi_M^{DE} > \Pi_M^{IE}$ for $d < \frac{\sqrt{2}-1}{1-\sqrt{2}\eta}\beta$, and $\Pi_M^{DE} \le \Pi_M^{IE}$ otherwise.

Proof of Proposition 5

Based on Table 6, the proof can be divided into two cases: (a). $\eta^T > \frac{d^T - 2\beta}{d^T}$, and (b). $\eta^T < \frac{d^T - 2\beta}{d^T}$.

(a). If $\eta^T > \frac{d^T - 2\beta}{d^T}$:

$\Pi_M^{DT} - \Pi_M^{IT} < 0$ for $d^T < \beta - \eta^T d^T$

If $\frac{d^T - 2\beta}{d^T} < \eta^T < \frac{d^T - 4\beta + 2\sqrt{2}\beta}{d^T}$, then $\Pi_M^{DT} - \Pi_M^{IT} < 0$ for $\beta - \eta^T d^T < d^T < 3\beta - d^T$.

If $\eta^T > \frac{d^T - 4\beta + 2\sqrt{2}\beta}{d^T}$, then $\Pi_M^{DT} - \Pi_M^{IT} < 0$ for $\beta - \eta^T d^T < d^T < 2\sqrt{2}\beta - \beta - \eta^T d^T$, while $\Pi_M^{DT} - \Pi_M^{IT} > 0$ for $2\sqrt{2}\beta - \beta - \eta^T d^T < d^T < 3\beta - d^T$.

If $\frac{d^T-2\beta}{d^T}<\eta^T<\frac{d^T-4\beta+2\sqrt{2}\beta}{d^T}$, then $\Pi_M^{DT}-\Pi_M^{IT}<0$ for $3\beta-d^T<d^T<\left(1+\sqrt{2}\right)\left(1-\sqrt{2}\eta^T\right)d^T-\beta$, while $\Pi_M^{DT}-\Pi_M^{IT}>0$ for $d>\left(1+\sqrt{2}\right)\left(1-\sqrt{2}\eta^T\right)d^T-\beta$.

If $\eta^T>\frac{d^T-4\beta+2\sqrt{2}\beta}{d^T}$, then $\Pi_M^{DT}-\Pi_M^{IT}>0$ for $d^T>3\beta-d^T$.

(b). If $\eta^T<\frac{d^T-2\beta}{d^T}$:

$\Pi_M^{DT}-\Pi_M^{IT}<0$ for $d^T<\beta-\eta^T d^T$

If $\eta^T<\frac{d^T+2\beta-2\sqrt{2}\beta}{d^T}$, then $\Pi_M^{DT}-\Pi_M^{IT}<0$ for $\beta-\eta^T d^T<d^T<\left(1+\sqrt{2}\right)\left(1-\sqrt{2}\eta^T\right)d^T-\beta$, while $\Pi_M^{DT}-\Pi_M^{IT}>0$ for $d>\left(1+\sqrt{2}\right)\left(1-\sqrt{2}\eta^T\right)d^T-\beta$

If $\eta^T>\frac{d^T+2\beta-2\sqrt{2}\beta}{d^T}$, then $\Pi_M^{DT}-\Pi_M^{IT}<0$.

Proof of Proposition 6

Based on Table 7, it is obvious to see that $\Pi_M^{DQ}<\Pi_M^{IQ}$ for $d\le\beta$ or $\beta<d\le 3\beta$, while $\Pi_M^{DQ}<\Pi_M^{IQ}$ for $d>3\beta$.

Proof of Proposition 7

Part (a) and (c) directly follow from the "Manufacturer's profit" in Table 8. For part (b), we have

$$\Pi_M^{DEn}-\Pi_M^{IEn}=\frac{-\left(7\beta^2-2\beta d+4\beta d\mu-2d^2\mu-d^2\right)\alpha^2}{2\left(d\mu+4\beta\right)\left(d\mu+\beta+d\right)},\ \text{for } \beta<d\le 3\beta.$$

Algebraic calculation shows that $\Pi_M^{DEn}-\Pi_M^{IEn}>0$ if $\frac{\left(2\mu-1+\sqrt{4\mu^2+10\mu+8}\right)\beta}{2\mu+1}<d\le 3\beta$, and $\Pi_M^{DEn}-\Pi_M^{IEn}\le 0$ otherwise, with equality if and only if $d=\frac{\left(2\mu-1+\sqrt{4\mu^2+10\mu+8}\right)\beta}{2\mu+1}$.

Proof of Proposition 9

We already have $d^{II}<d^{ID}<d^{DD}$, which readily gives all the "= 0" and "> 0" parts. It then suffices to prove $t^{II}>t^{ID}$ for $d>d^{ID}$, and $t^{ID}>t^{DD}$ for $d>d^{DD}$. Comparing Eq. (18) and Eq. (24) for $d>d^{ID}$, we have

$$t^{II}-t^{ID}=\frac{\beta(2-\theta)\left(1-\theta^2\right)\begin{bmatrix}(2+\theta)\left(6+\theta-3\theta^2\right)d\\+\beta(1+\theta)\left(4+4\theta-\theta^2-2\theta^3\right)\end{bmatrix}\alpha}{\left[2d+\beta(1+\theta)\right]X}>0.$$

Comparing Eq. (24) and Eq. (30) for $d>d^{DD}$, we have

$$t^{ID}-t^{DD}=\frac{\beta(2-\theta)\left(1-\theta^2\right)\begin{bmatrix}(2+\theta)\left(4+\theta-2\theta^2\right)\left(6+\theta-3\theta^2\right)d\\+\beta(1+\theta)\left(32+20\theta-28\theta^2-13\theta^3+6\theta^4+2\theta^5\right)\end{bmatrix}\alpha}{\left(2-\theta^2\right)\left[2d+\beta(1+\theta)\right]X}>0.$$

This completes the proof.

Proof of Proposition 10

We first prove that $\Pi_{M,2}^{II}>\Pi_{M,2}^{ID}$ holds for any θ and d. Comparing Table 9 for *II* and Table 10 for *ID*, we have the following results.

If $d\le d^{II}$, then

$$\Pi_{M,2}^{II}-\Pi_{M,2}^{ID}=\frac{(1-\theta)\left(4-3\theta^2\right)\alpha^2}{4\beta(1+\theta)(2-\theta)^2\left(2-\theta^2\right)}>0;$$

If $d^{II}<d\le d^{ID}$, then

$$\Pi_{M,2}^{II}-\Pi_{M,2}^{ID}=\frac{(1-\theta)\left[(1+\theta)^2\left(14-9\theta-8\theta^2+4\theta^3\right)\beta^2-\left(8+12\theta+4\theta^2\right)\beta d-(8+4\theta)d^2\right]\alpha^2}{4\beta(1+\theta)(2-\theta)\left(2-\theta^2\right)\left[\beta(1+\theta)+2d\right]^2}>0;$$

If $d>d^{ID}$, then

$$\Pi_{M,2}^{II}-\Pi_{M,2}^{ID}=\frac{\beta\left(1-\theta^2\right)\left(A_1d^2+A_2d+A_3\right)\alpha^2}{X^2\left[2d+\beta(1+\theta)\right]^2}>0,$$

where

$$A_1=\left(6+\theta-3\theta^2\right)^2\left(4+12\theta-11\theta^2-6\theta^3+5\theta^4\right)>0,$$

$$A_2=2\beta(1+\theta)\left(6+\theta-3\theta^2\right)^2\left(4+4\theta-7\theta^2-\theta^3+2\theta^4\right)>0,$$

$$A_3=\beta^2(1+\theta)^2\left(112+64\theta-248\theta^2-72\theta^3+195\theta^4+22\theta^5-62\theta^6-2\theta^7+7\theta^8\right)>0.$$

We now prove that $\Pi_{M,1}^{DD}<\Pi_{M,1}^{ID}$ holds if and only if $\theta<0.931$ and $d<d_1$. Comparing Table 10 for *ID* and Table 11 for *DD*, we have the following results.

If $d\le d^{ID}$, then

$$\Pi_{M,1}^{DD}-\Pi_{M,1}^{ID}=\frac{-(1-\theta)\left(128-320\theta^2+273\theta^4-96\theta^6+12\theta^8\right)\alpha^2}{4\beta(1+\theta)(2-\theta)^2\left(2-\theta^2\right)^2\left(4-\theta-2\theta^2\right)^2},$$

where the factor $\left(128-320\theta^2+273\theta^4-96\theta^6+12\theta^8\right)$ equals 0 at $\theta=0.931$, is positive if $\theta<0.931$, and is negative if $\theta>0.931$. Thus, within the range $d\le d^{ID}$, it holds $\Pi_{M,1}^{DD}<\Pi_{M,1}^{ID}$ if and only if $\theta<0.931$.

If $d^{ID}<d\le d^{DD}$, then

$$\Pi_{M,1}^{DD}-\Pi_{M,1}^{ID}=\frac{(1-\theta)\left(A_4d^2+A_5d+A_6\right)\alpha^2}{\beta(1+\theta)(2-\theta)\left(4-\theta-2\theta^2\right)^2X^2},$$

where

$$A_4 = (2+\theta)(2-\theta^2)(6+\theta-3\theta^2)^4 > 0,$$

$$A_5 = 2\beta(1+\theta)(2+\theta)(2-\theta^2)(6+\theta-3\theta^2)^2(20+4\theta-19\theta^2-\theta^3+4\theta^4) > 0,$$

$$A_6 = 2\beta^2(1+\theta)^2 \begin{pmatrix} -8416+2256\theta+28352\theta^2-7696\theta^3-38890\theta^4 \\ +11127\theta^5+27872\theta^6-8553\theta^7-11016\theta^8+3636\theta^9 \\ +2276\theta^{10}-804\theta^{11}-192\theta^{12}+72\theta^{13} \end{pmatrix}.$$

Solving the quadratic equation $A_4 d^2 + A_5 d + A_6 = 0$ with respect to d gives two roots, the smaller one being negative and the greater one given by d_1. Thus, it holds $A_4 d^2 + A_5 d + A_6 < 0$ if and only if $d < d_1$. Algebraic calculation shows that $d_1 = d^{ID}$ if $\theta = 0.931$, $d_1 < d^{ID}$ if $\theta > 0.931$, and $d^{ID} < d_1 < d^{DD}$ if $\theta < 0.931$. Therefore, within the range $d^{ID} < d \le d^{DD}$, it holds $A_4 d^2 + A_5 d + A_6 < 0$ and thereby $\Pi_{M,1}^{DD} < \Pi_{M,1}^{ID}$ if and only if $\theta < 0.931$ and $d < d_1$.

If $d > d^{DD}$, then

$$\Pi_{M,1}^{DD} - \Pi_{M,1}^{ID} = \frac{\beta(1-\theta^2)(A_7 d^2 + A_8 d + A_9)\alpha^2}{X^2(2-\theta^2)\left[2d+\beta(1+\theta)\right]^2} > 0,$$

where

$$A_7 = (6+\theta-3\theta^2)^2(16-16\theta+8\theta^2+28\theta^3-21\theta^4-10\theta^5+7\theta^6) > 0,$$

$$A_8 = 2\beta(1+\theta)(6+\theta-3\theta^2)^2(16-16\theta-4\theta^2+24\theta^3-11\theta^4-7\theta^5+4\theta^6) > 0,$$

$$A_9 = 2\beta^2(1+\theta)^2 \begin{pmatrix} 224-160\theta-396\theta^2+476\theta^3+179\theta^4 \\ -464\theta^5+51\theta^6+184\theta^7-54\theta^8-26\theta^9+10\theta^{10} \end{pmatrix} > 0.$$

This completes the proof.

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