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Pricing Policies of a Dual-Channel Supply Chain Considering Channel Environmental Sustainability

Shan Chen [1], Xu Wang [1,*], Yingbo Wu [2] and Fuli Zhou [1]

[1] School of Mechanical Engineering, Chongqing University, Chongqing, 400030, China; mt.chsha@gmail.com (S.C.); deepbreath329@outlook.com (F.Z.)
[2] School of Software Engineering, Chongqing University, Chongqing, 400030, China; wyb@cqu.edu.cn
* Correspondence: wx921@163.com; Tel.: +86-23-6510-6366

Academic Editor: Yongrok Choi
Received: 12 September 2016; Accepted: 28 February 2017; Published: 5 March 2017

Abstract: This paper examines the dual-channel supply chain in which the differentiation of the environmental sustainability of channels is considered. We analyze the influences of the level of environmental sustainability of channels on the pricing policies for the supply chain members in both centralized and decentralized models using the Stackelberg game model under inconsistent price policy. We obtain the optimal level of environmental sustainability of channels and pricing decisions for the players in the centralized and decentralized dual-channel supply chains. Results show that the influence mechanisms of the level of environmental sustainability of channels on the pricing decisions are different in the centralized and decentralized models. Furthermore, numerical analysis has been conducted to investigate the effects of the cross-environmental-sustainability sensitivity factor and the initial proportion of consumers who prefer the retail channel on the level of environmental sustainability of channels, pricing policies and players' profits.

Keywords: dual-channel supply chain; environmental sustainability; pricing policies

1. Introduction

In the recent decade, e-commerce has greatly developed and contributed to the wide adoption of the dual-channel supply chain by focal firms by the computer industry, cosmetic manufacturers, beverage and food manufacturers, sports goods producers and electronic goods manufacturers [1]. A dual-channel supply chain comprises a manufacturer's direct sale channel selling products directly online and a retailer's traditional retail channel selling products offline. Given the convenience of e-commerce, the dual-channel supply chain provides an alternative access for consumers to obtain products and helps the manufacturer to attract diverse kinds of consumers. On the other hand, consumers' attitudes toward e-commerce, such as consumer's environmental awareness (CEA), deeply influence their choice of whether to purchase products online or offline. An article in 2010 showed that 17% of U.S. consumers and 23% of European consumers are willing to pay more for environmentally friendly products [2]. A report conducted by the European Commission in 2014 pointed out a more optimistic situation that 75% of respondents agree that they are willing to buy environmentally-friendly products, even if it costs a little more to do so [3]. Environmentally-aware consumers whose population size is growing rapidly make purchase decisions with a trade-off between the product price, channel preference and environmental sustainability issues. The number of consumers who are willing to pay a higher price for eco-friendly products is positively related to the consumer's environmental awareness [4]. To the dual-channel supply chain system, a channel with a higher level of environmental sustainability would be more attractive to environmentally-aware consumers. Therefore, environmental sustainability would be a key characteristic of the development of the dual-channel supply chain especially when environmental sustainability has become significantly important in current society.

Literature has studied the environmental benefits of the online channel. Siikavirta et al. analyzed the direct and indirect potential of e-grocery for reducing greenhouse gas (GHG) emissions in the food production and consumption system [5]. Brown et al. performed a comparison of carbon emissions resulting from conventional shopping and online retailing and found that online retailing reduces more CO_2 emissions in certain conditions [6]. Similarly, Loon et al. suggested "online retailing can lower the environmental impact of shopping under specific circumstances" [7]. Their results showed the superiority of the online channel in reducing emissions. Some works examined other benefits of the online channel in cost saving. Matthews et al. compared the environmental impacts of online and traditional book retailing in the USA and suggested that e-commerce has a cost advantage and environmental benefit compared with traditional retailing [8]. Edwards et al. conducted a comparative study of CO_2 emissions for the home delivery and conventional shopping trips from the perspective of "last mile" and showed that e-commerce sales have a cost advantage and environmental benefits [9]. Environmental friendliness could be a significant characteristic of the online channel, thus, it would influence players' operational strategies.

Studies suggest that online business can benefit from their environmental sustainability practices. Online retailers could benefit from claiming that internet shopping is good for the environment [10]. Liu et al. found that retailers and manufacturers with superior eco-friendly operations benefit as consumer environmental awareness increases [11]. Once environmentally-aware consumers recognize the differences between the environment sustainability of online and traditional channels, those differences can be taken into consideration when they decide whether to shop online or offline. Manufacturers and retailers in the dual-channel supply chain are stimulated to fulfill eco-friendly practices that include the improvement of channel environmental sustainability.

Scholars have developed the dual-channel supply chain from the perspective of sustainability that integrates the environmental, social and economic criteria and allows an organization to achieve long-term economic viability in the field of sustainable supply chains [12]. Li et al. examined a dual-channel supply chain where the manufacturer made green products [13]. Modak et al. introduced a corporate social responsible (CSR) dual-channel supply chain [14]. They focused on green products and CSR in the dual-channel supply chain. Another stream related to this subject is the closed-loop dual-channel supply chain. Liu et al. developed a quality-based price competition model for the waste electrical and electronic equipment (WEEE) recycling market in a dual-channel environment [15]. Shu et al. studied the remanufacturing policies with the uncertainty of consumer preference [16]. Hong [17], Huang [18] and Zhang [19] researched the dual-channel closed-loop supply chain where environmental and social responsibilities had led manufacturers to used product recovery. However, few works consider the environmental sustainability of channels, whose differences have been analyzed and which has been shown to have an impact on the performances of the supply chain. Carrillo et al. studied the impacts of consumer environmental sensitivity on a dual-channel supply chain [20]. However, Carrillo's work ignored the effects of the environmental sustainability of channels. To analyze the effects of environmental sustainability on the performances of players, the paper integrates the environmental sustainability of channels into the dual-channel supply chain.

Literature has extensively studied the pricing policies between the manufacturer and the retailer in a dual-channel supply chain. Chiang et al. showed the channel conflict in the dual-channel supply chain and explored how optimal pricing policies could reduce the effect of double marginalization [21]. Ding et al. examined the pricing decisions of the dual-channel supply chain using the Stackelberg game model led by the manufacturer under several operational strategies [22]. Li et al. investigated the pricing policies of a competitive green dual-channel supply chain using a Stackelberg game model led by the manufacturer in the centralized and decentralized models [13]. Scholars analyzed the pricing policies of the dual-channel supply chain in the centralized and decentralized models and have drawn meaningful insights from the comparison of those results. Compared with Li's study, the paper integrates the environmental sustainability into the pricing policies in a dual-channel supply chain under the centralized and decentralized models by applying the Stackelberg game model led by the manufacturer. Further, the paper examines the relationship between the environmental sustainability of channels and the pricing policies of players and explains how the environmental sustainability of channels impacts the performances of the dual-channel supply chain by comparing the analysis results derived from the centralized and decentralized models.

This paper is organized as follows. Section 2 introduces the notations, assumptions and models. In Section 3, we examine the optimal level of environmental sustainability of channels and the pricing policies for the manufacturer and the retailer in both centralized and decentralized dual-channel supply chains. In Section 4, we show the results of numerical examples that are conducted to investigate the influences of the cross-environmental-sustainability sensitivity factor and the initial proportion of consumers who prefer the retailer channel on the optimal level of environmental sustainability of channels and the pricing policies of players in the two models. Section 5 gives the conclusions and directions for future study.

2. Model Formulation

This paper considers a dual-channel supply chain consisting of a manufacturer and a retailer where the manufacturer only produces one kind of product which can be sold through the traditional retail channel operated by the retailer and the direct sale channel operated by the manufacturer. The manufacturer and the retailer are risk-neutral and have access to the same information [13,19]. The retail channel and the direct sale channel are competitive in the product selling price and the channel environmental sustainability.

We assume that consumers are sensitive to the product price and environmental sustainability, thus, whether consumers buy product from the traditional retail channel or the direct sale channel will depend on their preference. Consumers will shift from a channel to its competitive channel when its environmental sustainability is impaired or the environmental sustainability of its competitive channel is improved, and when the selling price of a channel increased or the selling price of its competitive channel decreased. We take the linear demand model [13,23] where the channel demand is linear with the retail price, direct sale price, the level of environmental sustainability of retail channel and the level of environmental sustainability of direct sale price. The demand functions of the retail channel and the direct sale channel which are similar to Zhang's model [23], are as follows.

$$D_r = \rho\alpha - \beta p_r + \lambda p_d + \delta\theta_r - \mu\theta_d \tag{1}$$

$$D_d = (1-\rho)\alpha - \beta p_d + \lambda p_r + \delta\theta_d - \mu\theta_r \tag{2}$$

where D_r and D_d are the demands for products in the retail channel and the direct sale channel, respectively. In addition, the demands are assumed to be deterministic and are equal to the quantity sold by each channel. p_r is the retail price of the retail channel and p_d is the direct sale price of the direct sale channel, whereas $p_r \neq p_d$ indicates that the dual-channel supply chain takes an inconsistent price policy widely adopted by researchers [1,24,25]. α is the potential demand for the market. ρ $(0 < \rho < 1)$ is the initial proportion of consumers who prefer the retail channel, while $1-\rho$ denotes the initial proportion of consumers who prefer the direct sale channel. θ_r and θ_d denote the level of environmental sustainability of the retail channel and the direct sale channel respectively. β is the price sensitivity factor and λ is the cross-price sensitivity factor, whereas $\beta > \lambda > 0$ indicates that the channel's own price has greater influence on the channel demand than the competitive channel's price. δ is the channel's environmental sustainability sensitivity factor and μ is the cross-environmental-sustainability sensitivity factor, whereas $\delta > \mu > 0$ indicates that the level of environmental sustainability of a channel is more important than the level of environmental sustainability of the competitive channel. The quantity relationship between β and δ reflects whether the product price or the environmental sustainability has a greater influence on the channel's demand. To simplify the model, we assume that the product price and environmental sustainability of a channel have the same influence on demands as that that of consumers actively who are concerned about environmental issues. We suppose $\beta = \delta = 1$, which will not influence the final results. In addition, we note that consumers more easily perceive the differentiations of selling price between channels than the differentiations of environmental sustainability between channels, so we suppose $0 < \mu < \lambda < 1$. The easier it is for consumers to recognize the environmental sustainability of channels, the stronger the perception of the differences of environmental sustainability between the retail channel and the direct sale channel, and the smaller the difference between μ and λ. However, the harder it is for consumers to recognize the environmental sustainability of channels, the weaker the perception of the differences of environmental sustainability between channels, and the greater of difference between μ and λ. The simplified demand functions are as follows:

$$D_r = \rho\alpha - p_r + \lambda p_d + \theta_r - \mu\theta_d \tag{3}$$

$$D_d = (1-\rho)\alpha - p_d + \lambda p_r + \theta_d - \mu\theta_r \tag{4}$$

To maintain the environmental sustainability of channels in a certain level, the manufacturer has to pay extra cost $c(\theta_d)$ responding to the direct sale channel and the retailer has to pay extra cost $c(\theta_r)$ responding to the retail channel where η_d and η_r are the cost factor of the channel environmental sustainability. The costs are assumed to be a quadratic function of environmental sustainability [13]. We noted that the inconsistency of η_d and η_r would discourage the manufacturer or the retailer from improving the channel environmental sustainability and that it is important to make sure that there is a same baseline where the unit costs to improve the environmental sustainability of online and offline channels are equal. Thus, we assume the cost factors of the environmental sustainability of the online and offline channels are equal, namely $\eta_d = \eta_r = \eta$.

$$c(\theta_d) = \frac{\eta_d\theta_d^2}{2} \tag{5}$$

$$c(\theta_r) = \frac{\eta_r\theta_r^2}{2} \tag{6}$$

π_r and π_m denote the retailer's profits and the manufacturer's profits respectively. In the dual-channel supply chain, the manufacturer produces products at unit production cost c, wholesales it at wholesale price w to the retailer and sells it to the end consumers at the direct sale price p_d. The retailer purchases products from the manufacturer at wholesale price w and sells it to consumers at the retail price p_r. Thus, the profit functions of π_r and π_m are as follows:

$$\begin{aligned}\pi_r &= (p_r - w)D_r - c(\theta_r) \\ &= (p_r - w)(\rho\alpha - p_r + \lambda p_d + \theta_r - \mu\theta_d) - \tfrac{1}{2}\eta\theta_r^2\end{aligned} \tag{7}$$

$$\begin{aligned}\pi_m &= (w - c)D_r + (p_d - c)D_d - c(\theta_d) \\ &= (w - c)(\rho\alpha - p_r + \lambda p_d + \theta_r - \mu\theta_d) \\ &\quad + (p_d - c)((1-\rho)\alpha - p_d + \lambda p_r + \theta_d - \mu\theta_r) - \tfrac{1}{2}\eta\theta_d^2\end{aligned} \tag{8}$$

To simplify the model, we suppose $c = 0$, which will not affect the final results. The simplified manufacturer's profit function is as follows:

$$\begin{aligned}\pi_m &= wD_r + p_dD_d - c(\theta_d) \\ &= w(\rho\alpha - p_r + \lambda p_d + \theta_r - \mu\theta_d) + p_d[(1-\rho)\alpha - p_d + \lambda p_r + \theta_d - \mu\theta_r] - \tfrac{1}{2}\eta\theta_d^2\end{aligned} \tag{9}$$

3. Model Solution

This section derives the optimal level of environmental sustainability of channels and the pricing policies for the manufacturer and the retailer in the centralized and decentralized dual-channel supply chains respectively.

3.1. Centralized Dual Channel

In the centralized model, the manufacturer and the retailer are vertically integrated to make decisions to maximize the overall profits of the supply chain. Decision problems the central controller face are to deciding the retail price, the direct sale price and the level of environmental sustainability of channels simultaneously. π_s^C denotes the total profits of the dual-channel supply chain.

$$\pi_s^C = (p_r - w)D_r - c(\theta_r) + wD_r + p_dD_d - c(\theta_d) = p_rD_r + p_dD_d - c(\theta_r) - c(\theta_d) \tag{10}$$

Proposition 1: π_s^C is jointly concave to p_r, p_d and θ_r, θ_d respectively, but not jointly concave to p_r, p_d, θ_r and θ_d (Appendix A).

Proposition 1 indicates that the optimal values of p_r, p_d, θ_r and θ_d cannot be derived solely from the first-order condition. Following the two-stage approach, we can derive the optimal solution of p_r, p_d, θ_r and θ_d. In the first stage, we differentiate the π_s^C with respect of p_r and p_d in Equation (10), thus p_r and p_d with regard to θ_r and θ_d can be derived.

$$p_d^C(\theta_r^C, \theta_d^C) = \frac{(\lambda - \mu)\theta_r^C + (1 - \lambda\mu)\theta_d^C + (1 - \rho)\alpha + \lambda\rho\alpha}{2(1 - \lambda^2)} \tag{11}$$

$$p_r^C(\theta_r^C, \theta_d^C) = \frac{(1 - \lambda\mu)\theta_r^C + (\lambda - \mu)\theta_d^C + \rho\alpha + (1 - \rho)\lambda\alpha}{2(1 - \lambda^2)} \tag{12}$$

In the second stage, we substitute Equations (11) and (12) into Equation (10) and differentiate it with respect to θ_r and θ_d, thus we can get the optimal θ_r and θ_d.

$$\theta_r^C = \frac{\alpha\{2\eta[(\rho - 1)(\lambda\mu - 1) + \rho(\lambda - \mu)] - (1 - \mu^2)(1 - \rho + \rho\mu)\}}{[(1 + \mu)^2 - 2\eta(\lambda + 1)][(1 - \mu)^2 + 2\eta(\lambda - 1)]} \tag{13}$$

$$\theta_d^C = \frac{\alpha\{2\eta[\rho(\lambda - 1)(\mu + 1) + \mu - \lambda] + (1 - \mu^2)(\mu + \rho - \rho\mu)\}}{[2\eta(\lambda + 1) - (1 + \mu)^2][(1 - \mu)^2 + 2\eta(\lambda - 1)]} \tag{14}$$

Substituting Equations (13) and (14) into Equation (11) and (12), we can obtain p_d^C and p_r^C. We can also get π_s^C by substituting θ_r^C, θ_d^C, p_d^C and p_r^C into Equation (10).

Proposition 2:

(1) $\frac{\partial p_d^D}{\partial \theta_d^D} = \frac{\partial p_r^D}{\partial \theta_r^D} > 0$;

(2) $\frac{\partial p_d^D}{\partial \theta_r^D} = \frac{\partial p_r^D}{\partial \theta_d^D} > 0$;

(3) $\frac{\partial p_r^C}{\partial \theta_r^C} - \frac{\partial p_r^C}{\partial \theta_d^C} = \frac{\partial p_d^C}{\partial \theta_d^C} - \frac{\partial p_d^C}{\partial \theta_r^C} > 0$ (Appendix B).

Proposition 2 indicates that the retail price and the direct sale price increase as the level of channel environmental sustainability increases. The cross-effect of the level of environmental sustainability on channels is equal for the retail channel and the direct sale channel. In addition, the interaction between the level of environmental sustainability and the sale price within a certain channel is greater than the interaction between the level of environmental sustainability of a channel and the sale price of another channel. As there is only a decision maker, the manufacturer's and the retailer's optimal decisions are consistent to maximize the total profits of the supply chain system. The dual-channel supply chain will benefit from the improvement of the environmental sustainability.

3.2. Decentralized Dual Channel

In this model, the retailer and the manufacturer make decisions independently to maximize their own profits. We use the Stackelberg game led by the manufacturer to process this model. In the Stackelberg game led by the manufacturer, the manufacturer makes decisions on the wholesale price w, the direct sale price p_d and the level of environmental sustainability of direct channel θ_d at first as leader. The retailer determines the retail price p_r and the level of environmental sustainability of retail channel θ_r based on the decisions of the manufacturer as follows.

Proposition 3:

(1) π_r^D is jointly concave to p_r and θ_r;
(2) When $\eta > \frac{1}{2}$, π_m^D is jointly concave to p_d and θ_d, but is not jointly concave to p_d, θ_d and w (Appendix C).

Proposition 3 indicates that a large enough η is necessary for the optimization process. An important premise of the paper is that the effort to improve the channel environmental sustainability requires a lot of investment. Thus, the level of channel environmental sustainability becomes a key element of the pricing policies.

By the backward approach, we differentiate Equation (7) with respect to p_r and θ_r, then the retailer's optimal decisions of p_r^D and θ_r^D. regarding to p_d^D, w^D and θ_d^D are derived.

$$p_r^D(p_d^D, w^D, \theta_d^D) = \frac{\eta\rho\alpha + \eta\lambda p_d^D - \eta\mu\theta_d^D + (\eta-1)w^D}{2\eta-1} \tag{15}$$

$$\theta_r^D(p_d^D, w^D, \theta_d^D) = \frac{\rho\alpha + \lambda p_d^D - \mu\theta_d^D - w^D}{2\eta-1} \tag{16}$$

Using the two-stage optimization approach, we first substitute Equations (15) and (16) into Equation (9) and differentiate it with respect to p_d and θ_d, thus we can obtain p_d and θ_d with respect to w.

$$p_d^D(w^D) = \frac{\alpha(2\eta-1)[\mu\rho(\lambda-1)+(2\eta-1)(\rho-1)] + (\eta\lambda\mu^2+4\lambda\mu^2-\mu^3-4\eta\lambda+\lambda)w^D}{4(\lambda^2-2)\eta^3+(\lambda^2\mu^2-2\lambda^2-8\lambda\mu+12)\eta^2+(4\lambda\mu+4\mu^2-2\lambda\mu^3-6)\eta+(\mu^2-1)^2} \tag{17}$$

$$\theta_d^D(w^D) = \frac{\alpha(\eta\lambda\mu-\mu^2-2\eta+1)[(\eta\lambda-\mu)\rho+(2\eta-1)(\rho-1)] + (\mu-\lambda)[(2\eta-1)^2+\eta\lambda\mu-\mu^2]w^D}{4(\lambda^2-2)\eta^3+(\lambda^2\mu^2-2\lambda^2-8\lambda\mu+12)\eta^2+(4\lambda\mu+4\mu^2-2\lambda\mu^3-6)\eta+(\mu^2-1)^2} \tag{18}$$

At the second stage, we substitute Equations (15)–(18) into Equation (9), then we obtain w^D.

$$w^D = \frac{\{\eta\lambda^2+[4\eta^2+(\mu^2-2\mu-4)\eta-\mu+1]\lambda+\mu^2(2-\mu)-(2\eta-1)^2\}\rho-[(2\eta-1)^2+\eta\mu^2]\lambda+\mu^3}{8(\lambda^2-1)\eta^2+2[(\lambda\mu-2)^2+\mu^2-2\lambda^2]\eta-2\lambda\mu^3+3\mu^2+\lambda^2-2}\alpha$$

Substituting w^D into Equations (17) and (18), we can get p_d^D and θ_d^D. We can obtain p_r^D and θ_r^D by substituting w^D, p_d^D and θ_d^D into Equations (15) and (16). Finally, we can get π_r^D, π_m^D by substituting w^D, p_d^D, θ_d^D, p_r^D and θ_r^D into Equations (7) and (9).

Proposition 4:

(1) $\frac{\partial p_r^D}{\partial \theta_d^D} < 0$;
(2) $\frac{\partial p_d^D}{\partial \theta_r^D} > 0$ (Appendix D)

Proposition 4 indicates a different cross-effect among the level of environmental sustainability and the sale price between channels compared to the centralized model, in which the retail price will decrease when the environmental sustainability of the direct sale channel is improved, but the direct sale price will increase when the environmental sustainability of the retail channel is improved. As the manufacturer is the leader and the retailer is the follower in the decentralized dual-channel supply chain, the manufacturer will benefit from the improvement of the environmental sustainability of the retail channel, but the retailer will be squeezed by the improvement of the environmental sustainability of the direct sale channel.

Comparing the analyses in Sections 3.1 and 3.2, we can find that players' profit motivations significantly affect its pricing policies and environmental sustainability strategies. In the centralized model, the central controller keeps the coordinated decisions of the manufacturer and the retailer to avoid channel conflicts. In the decentralized model, there are channel conflicts in the players' pricing policies and environmental sustainability strategies because of players' self-interest maximization motivations and their unequal status. If the level of environmental sustainability of the retail channel improved, the manufacturer will benefit from it and set a higher direct sale price. However, if the level of environmental sustainability of the direct channel improves, the retailer has to take the price discount strategy to compete with the direct sale channel. As the leader and the main beneficiary, the manufacturer has the primary responsibility for improving environmental sustainability of the dual-channel supply chain.

4. Numerical Example

In this section, we present numerical simulations to illustrate the analytical results of those two models above. We illustrate the effects of the cross-environmental-sustainability sensitivity factor and the initial proportion of consumers who prefer the retail channel on the analytical results in both centralized and decentralized dual-channel supply chains. The related parameters are assumed to be $\alpha = 200$, $\lambda = 0.8$ and $\eta = 5$.

4.1. The Cross-Environmental-Sustainability Sensitivity Factor

In this subsection, we analyze the impacts of the cross-environmental-sustainability sensitivity factor at the level of environmental sustainability of the retail channel and the direct sale channel, as well as the retail price and the direct sale price in the centralized and decentralized dual-channel supply chains.

From Figure 1, for a fixed $\rho = 0.4$, the optimal level of environmental sustainability of the retail channel and the direct sale channel, the optimal retail price and the optimal direct sale price decrease with the increase of the cross-environmental-sustainability sensitivity factor in the centralized model. The differences of the manufacturer's and the retailer's optimal decisions are very small. When μ is small, which means consumer perception of environmental sustainability of channels is poor, a relatively high level of environmental sustainability of channels is advantageous to allure environmentally-aware consumers, and the system gains high profits. However, when μ is large, which means consumer perception of the environmental sustainability of channels is strong, the supply chain system keeps the channel environmental sustainability in a rather low level and the system obtains a low profit.

From Figure 1, similar to the negative correlation in the centralized model, the optimal level of environmental sustainability of the retail channel and the direct sale channel decreases with the increase of the environmental sustainability sensitivity factor in the decentralized model, as well as the optimal retail price and the optimal direct sale price. However, the optimal level of environmental sustainability of the direct channel is apparently better than the retail channel. However, this gap narrows as μ increases. When μ is relatively small, which means consumer perception of difference in environmental sustainability between channels is poor, a relatively high level of environmental sustainability of the direct sale channel is beneficial to strengthen consumer recognition of the superiority of the direct sale channel in environmental friendliness. However, when μ is relatively large, which means consumer perception of difference of environmental sustainability between channels is strong, a slightly high level of environmental sustainability of the direct sale channel is enough to attract consumers.

Comparing the centralized and decentralized models, we show that there are negative correlations between θ_r, θ_d, p_r, p_d and μ. However, the magnitudes of changes in the centralized model are greater than in the decentralized model. The optimal level of environmental sustainability of the retail channel in the centralized model is always greater than it in the decentralized model. However, if the cross-environmental-sustainability sensitivity factor is above a threshold, the optimal level of environmental sustainability of the direct channel in the decentralized model is greater than in the centralized model. It means that in a certain situation, the decentralized model performs better than the centralized model in some aspects. In addition, the effect of double marginalization declines with the increase of the environmental sustainability sensitivity factor, however, the profits of players and the total supply chain also decrease. In addition, the optimal level of environmental sustainability of retail channel in the centralized model is significantly higher than in the decentralized model. This reflects that the retailer is reluctant to maintain a high level of environmental sustainability of the retail channel due to the unequal status of the manufacturer and the retailer.

4.2. The Initial Proportion of Consumers Who Prefer the Retail Channel

In this subsection, we examine the effects of the initial proportion of consumers who prefer the retail channel on the level of environmental sustainability of the retail channel and the direct sale channel, the retail price and the direct sale price in the centralized and decentralized dual-channel supply chains.

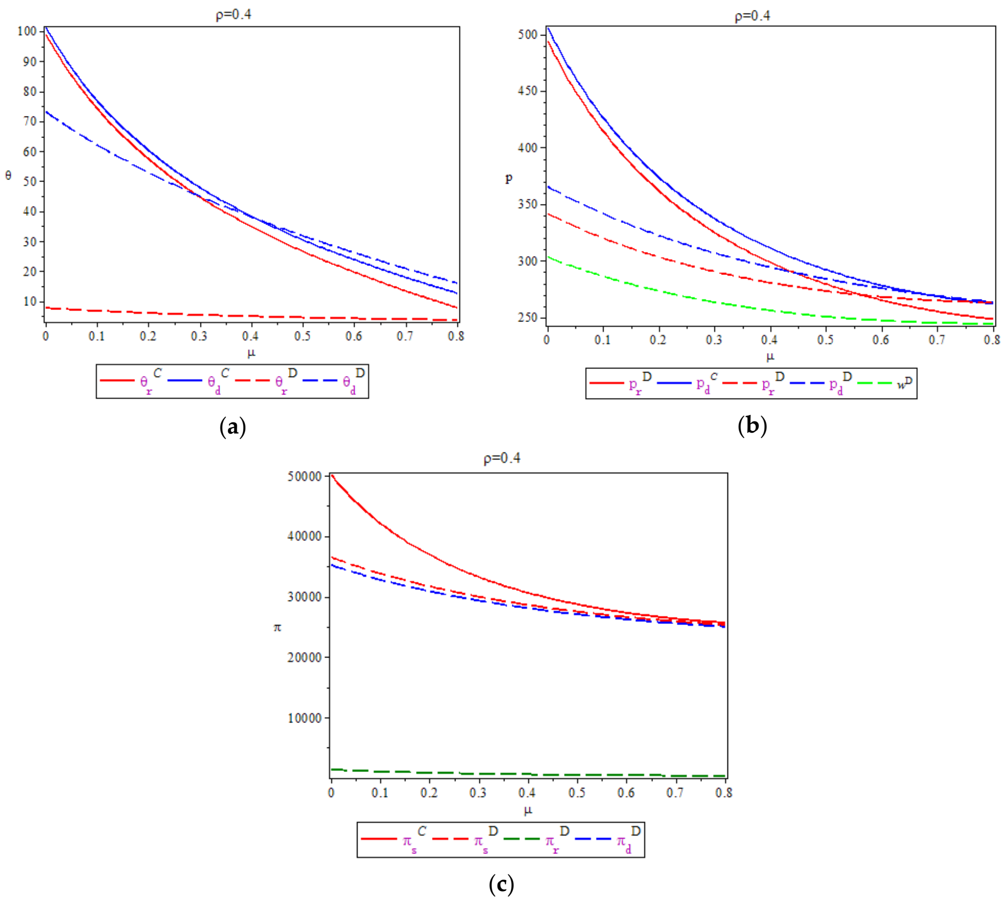

Figure 1. The illustrations of the effect of μ on the analytical results in the centralized and decentralized dual-channel supply chains when $\rho = 0.4$. (**a**) shows the effect of μ on the θ_r and θ_d; (**b**) illustrates the effect of μ on the p_r, p_d and w; and (**c**) displays the effect of μ on the π_s, π_r and π_m.

From Figure 2, for a fixed $\mu = 0.3$, if the initial proportion of consumers who prefer the retail channel increases, the optimal level of environmental sustainability of the retail channel and the optimal retail price will grow, but the optimal level of environmental sustainability of the direct sale channel and the optimal direct sale price will decrease in a centralized model. If ρ is above a threshold, the optimal level of environmental sustainability of the retail channel will be higher than the direct sale channel. These trends are also applied to the retail price and the direct sale price. This means the motivations for players to maintain a relatively high level of environmental sustainability depend on the consumers' potential demands in the centralized model.

From the Figure 2, the optimal level of environmental sustainability of the direct channel is apparently higher than the retail channel in the decentralized model, but the gap narrows with the increase of ρ. The optimal level of environmental sustainability of the direct sale channel decreases with the increase of ρ. However, the optimal level of environmental sustainability of the retail channel increases as ρ increases. This means that the retailer's willingness to improve environmental sustainability of the retail channel depends on the consumers' potential demands, but their willingness is lacking compared to the manufacturer's willingness to improve the environmental sustainability of the direct sale channel. The optimal whole sale price is positive with ρ. If ρ is lower than a threshold, the direct sale price will be higher than the retail price. However, if ρ is above a threshold, the retail price will be higher than the direct sale price. This also means that the optimal pricing decisions of the retailer and the manufacturer depend on consumer demands.

Comparing the two settings, we can find that the optimal level of environmental sustainability of channels, the retail price, the direct sale price and the total profit of the supply chain in the decentralized model are always lower than those in the centralized model. The double-marginalization effect not only affects the profits but also influences the environmental sustainability of the dual-channel supply chain.

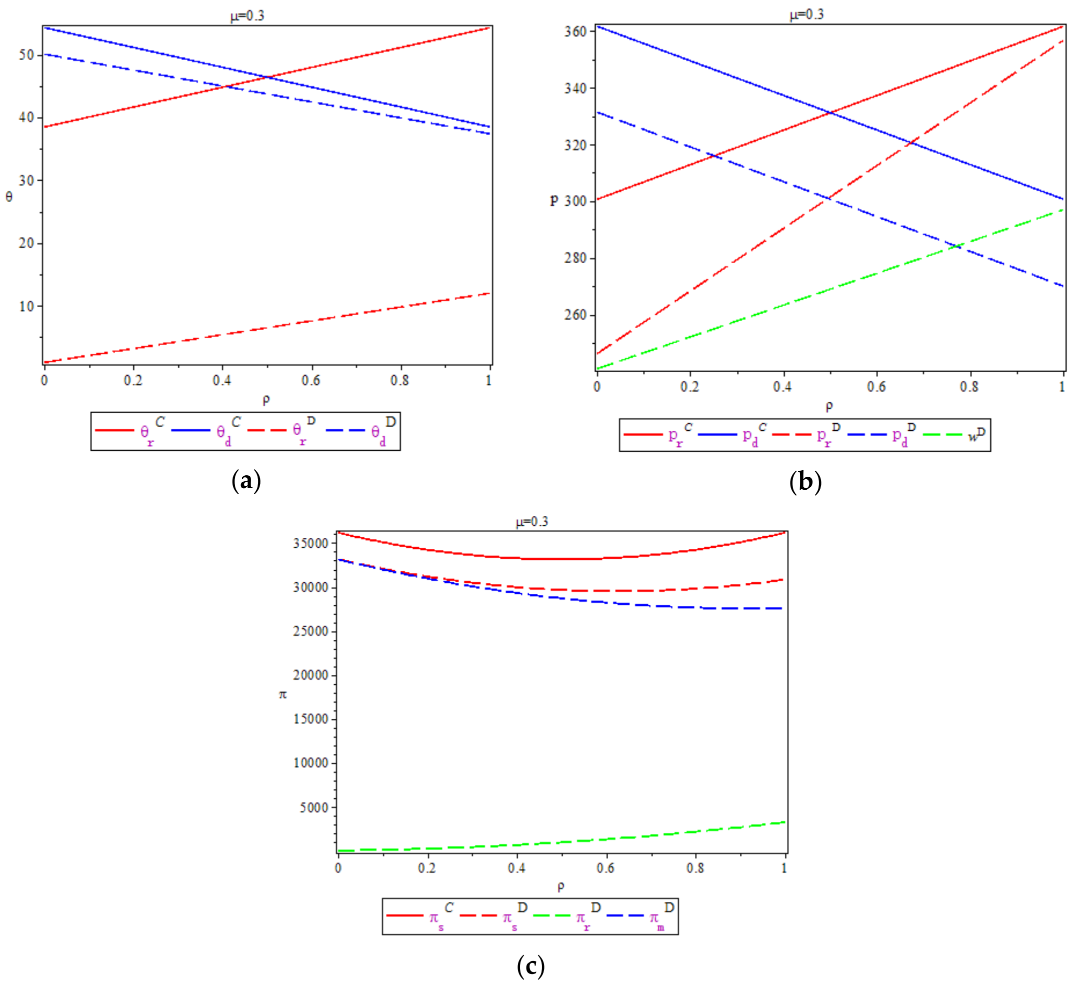

Figure 2. The illustrations of the impact of ρ on the analytical results in the centralized and decentralized dual-channel supply chains when $\mu = 0.3$. (**a**) shows the impact of ρ on the θ_r and θ_d; (**b**) illustrates the impact of ρ on the p_r, p_d and w; and (**c**) displays the impact of ρ on the π_r, π_d and π_s.

5. Conclusions

This paper integrates the channel environmental sustainability into the dual-channel supply chain and discusses the environmental sustainability strategies and pricing policies for the members in the centralized and decentralized models. Furthermore, we examine the impact of the level of environmental sustainability of channels on the manufacturer's and the retailer's pricing decisions. In addition, we analyze the cross-environmental-sustainability sensitivity factor and the initial proportion of consumers who prefer the retail channel on optimal environmental sustainability strategies and pricing policies of players by numerical examples.

Through the analyses above, we have some interesting findings that are different from earlier studies. The environmental sustainability of channels has significant impacts on the optimal pricing decisions of players in a dual-channel supply chain. However, our analyses show that the influence mechanisms are different in the centralized and decentralized models. In the centralized model, the retailer's and the manufacturer's decisions are consistent as there is only a decision maker, which results in the positive correlations between the level of environmental sustainability of channels and optimal prices of the supply chain system. However, the correlations are much more complex in the decentralized model not only because of the independently self-interested decisions of the manufacturer and the retailer but also because of the unequal status of the manufacturer and the retailer. In addition, we discovered that the optimal level of environmental sustainability of the direct sale channel is greater than the retail channel in the decentralized dual-channel supply chain, which is consistent with the analyses in the introduction. Moreover, we were surprised to find that all of the decision variables are negative correlated with the cross-environmental-sustainability sensitivity factor both in the centralized and decentralized models. The increase in consumers' perception of channel environmental sustainability will lead to the decrease of the environmental sustainability of the supply chain system. There are complex correlations between decision variables and the initial proportion of consumers who prefer the retail channel. From the numerical analyses, we found that there are thresholds of the initial proportion of consumers who prefer the retail channel where the optimal retail price is equal to the optimal direct sale price in the centralized and decentralized models. When the initial proportion of consumers who prefer the retail channel is relatively large, the retail price should be set greater than the direct sale price. Further, we noticed that the effect of double marginalization affects the total profits of the supply chain system as well as the environmental sustainability of the system. The cross-environmental-sustainability sensitivity factor and the initial proportion of consumers who prefer the retail channel have opposite influences on the double marginalization, which provides a new horizon for the players to diminish the effect of double marginalization.

In future research, some assumptions in this paper can be relaxed. For example, the product price and environmental sustainability in a certain channel may have unequal influences on consumer purchase behavior in practice. In addition, the risk attitudes of the manufacturer and the retailer to apply green technologies to improve environmental sustainability can be considered. It is worthwhile to take a comprehensive analysis of the impacts of the environmental sustainability of the supply chain system including the environmental sustainability of channels, products and services on the optimal strategies of the manufacturer and the retailer.

Acknowledgments: This study was supported by National Science and Technology Support Program of China under Grant No. 2015BAF05B03 and 2015BAH46F01, National Natural Science Foundation of China under Grant No. 71301177, National Science and Technology Mojor Project under Grant No. 2016ZX04004005, the Research Fund for the Doctoral Program of Higher Education under Grant No. 20130191110045, the Fundamental Research Funds for the Central Universities Project under Grant No. CDJZR13110048 and 106112015CDJSK02JD05, and the Chongqing City Key Science Program Project under Grant No. cstc2015yykfC60002.

Author Contributions: Shan Chen and Xu Wang conceived and designed the study; Yingbo Wu and Fuli Zhou contributed analysis tools; Shan Chen wrote the paper. All authors contributed to the discussions and interpretation of the results.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Taking the second-order partial differentiate of π_s^C with respect of p_r, p_d, θ_r and θ_d in Equation (7), we obtain the Hessian matrix.

$$\boldsymbol{H_s} = \begin{pmatrix} \frac{\partial^2 \pi_s}{\partial p_r^2} & \frac{\partial^2 \pi_s}{\partial p_r \partial p_d} & \frac{\partial^2 \pi_s}{\partial p_r \partial \theta_r} & \frac{\partial^2 \pi_s}{\partial p_r \partial \theta_d} \\ \frac{\partial^2 \pi_s}{\partial p_d \partial p_r} & \frac{\partial^2 \pi_s}{\partial p_d^2} & \frac{\partial^2 \pi_s}{\partial p_d \partial \theta_r} & \frac{\partial^2 \pi_s}{\partial p_d \partial \theta_d} \\ \frac{\partial^2 \pi_s}{\partial \theta_r \partial p_r} & \frac{\partial^2 \pi_s}{\partial \theta_r \partial p_d} & \frac{\partial^2 \pi_s}{\partial \theta_r^2} & \frac{\partial^2 \pi_s}{\partial \theta_r \partial \theta_d} \\ \frac{\partial^2 \pi_s}{\partial \theta_d \partial p_r} & \frac{\partial^2 \pi_s}{\partial \theta_d \partial p_d} & \frac{\partial^2 \pi_s}{\partial \theta_d \partial \theta_r} & \frac{\partial^2 \pi_s}{\partial \theta_d^2} \end{pmatrix} = \begin{pmatrix} -2 & 2\lambda & 1 & -\mu \\ 2\lambda & -2 & -\mu & 1 \\ 1 & -\mu & -\eta & 0 \\ -\mu & 1 & 0 & -\eta \end{pmatrix}$$

$$(-1)^i \boldsymbol{D_i}, i = 1,2,3,4$$

$$\boldsymbol{D}_1 = -(-2) = 2 > 0$$

$$\boldsymbol{D}_2 = \begin{vmatrix} \frac{\partial^2 \pi_s}{\partial p_r^2} & \frac{\partial^2 \pi_s}{\partial p_r \partial p_d} \\ \frac{\partial^2 \pi_s}{\partial p_d \partial p_r} & \frac{\partial^2 \pi_s}{\partial p_d^2} \end{vmatrix} = \begin{vmatrix} -2 & 2\lambda \\ 2\lambda & -2 \end{vmatrix} = 4(1-\lambda^2) > 0$$

$$\boldsymbol{D}_3 = (-1)^3 \begin{vmatrix} \frac{\partial^2 \pi_s}{\partial p_r^2} & \frac{\partial^2 \pi_s}{\partial p_r \partial p_d} & \frac{\partial^2 \pi_s}{\partial p_r \partial \theta_r} \\ \frac{\partial^2 \pi_s}{\partial p_d \partial p_r} & \frac{\partial^2 \pi_s}{\partial p_d^2} & \frac{\partial^2 \pi_s}{\partial p_d \partial \theta_r} \\ \frac{\partial^2 \pi_s}{\partial \theta_r \partial p_r} & \frac{\partial^2 \pi_s}{\partial \theta_r \partial p_d} & \frac{\partial^2 \pi_s}{\partial \theta_r^2} \end{vmatrix} = 4\eta\beta^2 - 2\beta\delta^2$$

$\boldsymbol{D}_3$ may be negative when δ is large enough, so π_s^C is not jointly concave with p_r, p_d and θ_r.

We consider that $\boldsymbol{H}_1$ and $\boldsymbol{H}_2$ are submatrices of $\boldsymbol{H_s}$.

$$\boldsymbol{H}_1 = \begin{pmatrix} \frac{\partial \pi_s^2}{\partial p_r^2} & \frac{\partial \pi_s^2}{\partial p_r \partial p_d} \\ \frac{\partial \pi_s^2}{\partial p_d \partial p_r} & \frac{\partial \pi_s^2}{\partial p_d^2} \end{pmatrix} = \begin{pmatrix} -2 & 2\lambda \\ 2\lambda & -2 \end{pmatrix}$$

$$\boldsymbol{H}_2 = \begin{pmatrix} \frac{\partial \pi_s^2}{\partial \theta_r^2} & \frac{\partial \pi_s^2}{\partial \theta_r \partial \theta_d} \\ \frac{\partial \pi_s^2}{\partial \theta_d \partial \theta_r} & \frac{\partial \pi_s^2}{\partial \theta_d^2} \end{pmatrix} = \begin{pmatrix} -\eta & 0 \\ 0 & -\eta \end{pmatrix}$$

$$\boldsymbol{D}_1 = -(-2) = 2 > 0$$

$$\boldsymbol{D}_2 = \begin{vmatrix} -2\beta & 2\lambda \\ 2\lambda & -2\beta \end{vmatrix} = 4(1-\lambda^2) > 0$$

Therefore, we can find that π_s^C is jointly strict concave with p_r and p_d.

Similarly, we can find that π_s^C is jointly strict concave with θ_r and θ_r

We differentiate the π_s^C in Equation (7) with respect to p_r^C and p_d^C, then we can obtain the optimal decision on p_r^C and p_d^C regarding θ_r^C and θ_d^C.

$$p_d^C(\theta_r^C, \theta_d^C) = \frac{(\lambda-\mu)\theta_r^C + (1-\lambda\mu)\theta_d^C + (1-\rho)\alpha + \lambda\rho\alpha}{2(1-\lambda^2)} \tag{A1}$$

$$p_r^C(\theta_r^C, \theta_d^C) = \frac{(1-\lambda\mu)\theta_r^C + (\lambda-\mu)\theta_d^C + \rho\alpha + (1-\rho)\lambda\alpha}{2(1-\lambda^2)} \tag{A2}$$

Substituting $p_d^C(\theta_r^C, \theta_d^C)$ and $p_r^C(\theta_r^C, \theta_d^C)$ into Equation (7) and differentiating it with respect to θ_r^C and θ_d^C, we can obtain the optimal decision on θ_r^C and θ_d^C.

$$\theta_r^C = \frac{\alpha\{2\eta[(\rho-1)(\lambda\mu-1) + \rho(\lambda-\mu)] - (1-\mu^2)(1-\rho+\rho\mu)\}}{[(1+\mu)^2 - 2\eta(\lambda+1)][(1-\mu)^2 + 2\eta(\lambda-1)]} \tag{A3}$$

$$\theta_d^C = \frac{\alpha\{2\eta[\rho(\lambda-1)(\mu+1)+\mu-\lambda]+(1-\mu^2)(\mu+\rho-\rho\mu)\}}{[2\eta(\lambda+1)-(1+\mu)^2][(1-\mu)^2+2\eta(\lambda-1)]} \tag{A4}$$

Appendix B

Differentiating Equation (A1) with respect to θ_r^C and θ_d^C, we obtain:

$$\frac{\partial p_r^C(\theta_r^C,\theta_d^C)}{\partial\theta_r^C} = \frac{\partial p_d^C(\theta_r^C,\theta_d^C)}{\partial\theta_d^C} = \frac{1-\lambda\mu}{2(1-\lambda^2)} > 0$$

$$\frac{\partial p_r^C(\theta_r^C,\theta_d^C)}{\partial\theta_d^C} = \frac{\partial p_d^C(\theta_r^C,\theta_d^C)}{\partial\theta_r^C} = \frac{\lambda-\mu}{2(1-\lambda^2)} > 0$$

$$\frac{\partial p_r^C(\theta_r^C,\theta_d^C)}{\partial\theta_r^C} - \frac{\partial p_r^C(\theta_r^C,\theta_d^C)}{\partial\theta_d^C} = \frac{\partial p_d^C(\theta_r^C,\theta_d^C)}{\partial\theta_d^C} - \frac{\partial p_d^C(\theta_r^C,\theta_d^C)}{\partial\theta_r^C} = \frac{1+\mu}{2(1+\lambda)} > 0$$

Appendix C

Taking the second-order partial differentiate of π_r^D with respect of p_r and θ_r in Equation (7), we obtain the Hessian matrix.

$$\boldsymbol{H}_{\pi_r} = \begin{pmatrix} \frac{\partial^2\pi_r}{\partial p_r^2} & \frac{\partial^2\pi_r}{\partial p_r\partial\theta_r} \\ \frac{\partial^2\pi_r}{\partial\theta_r\partial p_r} & \frac{\partial^2\pi_r}{\partial\theta_r^2} \end{pmatrix} = \begin{pmatrix} -2 & 1 \\ 1 & -2 \end{pmatrix}$$

Obviously, $\boldsymbol{H}_{\pi_r}$ is negative definite. Therefore, π_r^D is jointly concave with the p_r and θ_r.

Similarly, taking the second-order partial differentiate of π_m^D with respect to p_d, θ_d and w in Equation (9), we obtain the Hessian matrix.

$$\boldsymbol{H}_{\pi_m} = \begin{pmatrix} \frac{\partial^2\pi_m}{\partial p_d^2} & \frac{\partial^2\pi_r}{\partial p_d\partial w} & \frac{\partial^2\pi_r}{\partial p_d\partial\theta_d} \\ \frac{\partial^2\pi_r}{\partial w\partial p_d} & \frac{\partial^2\pi_m}{\partial w^2} & \frac{\partial^2\pi_r}{\partial w\partial\theta_d} \\ \frac{\partial^2\pi_r}{\partial\theta_d\partial p_d} & \frac{\partial^2\pi_r}{\partial\theta_d\partial w} & \frac{\partial^2\pi_m}{\partial\theta_d^2} \end{pmatrix} = \begin{pmatrix} -2 & \lambda & 1 \\ \lambda & 0 & -\mu \\ 1 & -\mu & -\eta \end{pmatrix}$$

As $\frac{\partial^2\pi_m}{\partial\theta_d^2} = 0$, π_m^D is not jointly concave with p_d, θ_d and w.

However, $\boldsymbol{H}_1 = \begin{pmatrix} \frac{\partial^2\pi_m}{\partial p_d^2} & \frac{\partial^2\pi_m}{\partial p_d\partial\theta_d} \\ \frac{\partial^2\pi_m}{\partial\theta_d\partial p_d} & \frac{\partial^2\pi_m}{\partial\theta_d^2} \end{pmatrix} = \begin{pmatrix} -2 & 1 \\ 1 & -\eta \end{pmatrix}$ is a negative definite when $\eta > \frac{1}{2}$.

Therefore, when $\eta > \frac{1}{2}$, π_m^D is jointly concave with p_d and θ_d.

We differentiate π_r in the Equation (7) with respect to p_r and θ_r, then we obtain the optimal value of p_r and θ_r regarding to p_d, θ_d and w.

$$p_r^D(p_d^D,w^D,\theta_d^D) = \frac{\eta\rho\alpha+\eta\lambda p_d^D-\eta\mu\theta_d^D+(\eta-1)w^D}{2\eta-1} \tag{A5}$$

$$\theta_r^D(p_d^D,w^D,\theta_d^D) = \frac{\rho\alpha+\lambda p_d^D-\mu\theta_d^D-w^D}{2\eta-1} \tag{A6}$$

Substituting Equations (A5) and (A6) into Equation (9) and differentiating it with p_d and θ_d, we can obtain the optimal value of p_d and θ_d responding to w.

$$p_d^D(w^D) = \frac{\alpha(2\eta-1)[\mu\rho(\lambda-1)+(2\eta-1)(\rho-1)]+(\eta\lambda\mu^2+4\lambda\mu^2-\mu^3-4\eta\lambda+\lambda)w^D}{4(\lambda^2-2)\eta^3+(\lambda^2\mu^2-2\lambda^2-8\lambda\mu+12)\eta^2+(4\lambda\mu+4\mu^2-2\lambda\mu^3-6)\eta+(\mu^2-1)^2} \tag{A7}$$

$$\theta_d^D(w^D) = \frac{\alpha(\eta\lambda\mu-\mu^2-2\eta+1)[(\eta\lambda-\mu)\rho+(2\eta-1)(\rho-1)]+(\mu-\lambda)[(2\eta-1)^2+\eta\lambda\mu-\mu^2]w^D}{4(\lambda^2-2)\eta^3+(\lambda^2\mu^2-2\lambda^2-8\lambda\mu+12)\eta^2+(4\lambda\mu+4\mu^2-2\lambda\mu^3-6)\eta+(\mu^2-1)^2} \tag{A8}$$

Substituting Equations (A7) and (A8) into Equation (9), then we differentiate π_m with respect to w. We obtain:

$$w^D = \frac{\{\eta\lambda^2+[4\eta^2+(\mu^2-2\mu-4)\eta-\mu+1]\lambda+\mu^2(2-\mu)-(2\eta-1)^2\}\rho-[(2\eta-1)^2+\eta\mu^2]\lambda+\mu^3}{8(\lambda^2-1)\eta^2+2[(\lambda\mu-2)^2+\mu^2-2\lambda^2]\eta-2\lambda\mu^3+3\mu^2+\lambda^2-2}\alpha$$

Substituting w^D into Equations (17) and (18), we can get p_d^D and θ_d^D. We can obtain p_r^D and θ_r^D by substituting w^D, p_d^D and θ_d^D into Equations (15) and (16). Finally, we can get π_r^D, π_m^D by substituting w^D, p_d^D, θ_d^D, p_r^D and θ_r^D into Equations (7) and (9).

Appendix D

From Equations (A5) and (A6), it is easy to obtain:

$$\frac{\partial p_r^D}{\partial \theta_d^D} = \frac{-\eta\mu}{2\eta-1} < 0$$

$$\frac{\partial p_d^D}{\partial \theta_r^D} = \frac{2\eta-1}{\lambda} > 0$$

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