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Complex Analysis on Dual Channel Green Supply Chain with Consistent Pricing Strategy

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Abstract. The paper investigates the dynamic green dual channel supply chain with consistent pricing strategy where the manufacturer produces a single kind of green product and sells it to end consumers directly through online channel besides the traditional retail channel. We focus on the complex features of these supply chain systems and how the players adjust their pricing and greening strategies in dynamic settings. We first derive the player's static optimal decisions of centralized and decentralized scenarios in a single period. Based on the static equilibrium decisions, we develop the dynamic centralized and decentralized model and explore the dynamic characteristics of those dynamic systems by numerical simulations. Numerical results suggest the optimal adjustment strategies of decision variables and players' profit in the dynamic environment. We find that the dynamic centralized/decentralized systems would be into chaos when the intertemporal adjustment speed of decision variables is over a threshold. Especially, the intertemporal adjustment speed of greenness degree is more sensitive than wholesale price and sale price.

Keywords: dual channel supply chain, dynamic, green product

1 Introduction

With the public's persistent attention on the environment issues, sustainable development has been recognized by industry and academy, which conduces to the continuously prosperous research on sustainable supply chain management [1]. The application of SSCM enables firms to create competitive advantage and improves the environmental and economic performance of organizations [2-3]. Therefore, organizations have held responsible for the environmental and social performance by major stakeholders [4-5].

Literatures have investigated efficient approaches to enhance sustainability of supply chain. Green products play a significant role in the development of SSCM with regard to the decision making process [6]. Green products are defined as new products that have significant greater greenness than conventional or competitive products [7]. Green innovation is regarded as a survival need for firms to keep competitiveness, especially in a green market where consumers' environmental awareness has been increasingly enforced [8]. On the other hand, establishment of direct channel has been approved to an efficient way to enhance supply chain sustainability. Researches have shown that online channel, compared to offline channel, has greater performance on sustainability [9]. Edwards et al. conducted a comparison study of CO_2 emission of online and offline channel and suggested that online channel is better in cost advantage and environmental benefit [10]. Indeed, the dual-channel supply chain has been

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widely adopted by focal firms where online and offline channel coexist. It is suggested that dual channel supply chain provides an alternative access for consumers to obtain products and helps the manufacturer to attract diverse kinds of consumers [11]. Therefore, on the perspective of sustainability improvement, it is advisable for the green manufacturer to adopt the structure of dual channel supply chain.

Researches on dual channel green supply chain have focused on the pricing problem. One stream studies the pricing problem of dual channel supply chain considering channel sustainability. Chen et al. developed pricing and sustainable problems in a dual channel supply integrating with channel sustainability [11]. Another stream studies the pricing problem of dual channel supply chain considering green product development. Li et al. examined the pricing and green policies of a competitive dual channel supply chain under consistent pricing policies [6]. Xu et al. investigated the pricing policies and coordination contract in the dual channel supply chain arising out of low-carbon preference and channel substitution [12]. However, studies above only focus on the pricing strategies in static setting, which ignoring the complexity of dynamic market environment. Particularly, the player's myopia in dynamic environment would influence their decisions significantly.

Previous literatures have explored the complex dynamic phenomena of the dual channel supply chain. Generally, players in the dual channel supply chain are assumed bounded rational in partial information environment. Zhang et al. explored the complex features of a dual channel supply chain where contains a fair neutral manufacturer and a fair caring retailer [13]. Ma et al. conducted the complex analyses of dual channel supply chain under uncertain demand [14]. Ma et al. examines the optimal decisions of dual-channel game model considering the inputs of retailing service [15]. Huang et al. studies the entropy complexity of an asymmetric dual channel supply chain considering consumer's attitude toward risks for probabilistic products and probabilistic selling [16]. Researches above only focus on the player's irrational behavior but ignore the characteristics of product that are the manufacturer's significant operation strategies. As far as we known, few studies investigate the complex features of dual channel supply chain with consideration of green product. Hence, we try to address the following research questions in this paper: (1) what are the complex features of a dual channel supply chain would be performed where green products are highlighted? (2) how these complex features would influence player's strategies adjustment?

Table 1. Comparison of the current research and the most related studies

Articles	Static Dual Channel Supply Chain			Dynamic Dual Channel Supply Chain			
	Price Factor	Non-Price Factor		Price Factor	Non-Price Factor		
		Channel Sustainability	Green Product		Participant's Behavior	Green Factor	Non-green Factor
Chen et al. [11]	✓	✓					
Xu et al. [12]	✓		✓				
Li et al. [6]	✓		✓				
Zhang et al. [13]				✓	✓		
Ma et al. [14]				✓	✓		Uncertain Demand
Ma et al. [15]				✓	✓		Retail Service
Huang et al. [16]				✓	✓		Probabilistic Selling
Current study				✓	✓	✓	

In this paper, a dual channel supply chain is examined, in which a manufacturer produces a kind of green product and sells it through a traditional retail channel as well as an online channel. We first obtain the static equilibrium solutions of the centralized/decentralized dual channel supply chain in a single period under consistent price policy. Based on the static solutions, we develop the dynamic centralized/ decentralized system and explore the equilibrium points of these dynamic systems. Then, we analysis whether these equilibrium points are stable or unstable by eigenvalue approach and Jury's condition. Finally, we examine the complex features of stable equilibrium points of these dynamic systems by numerical simulation. We find that the dynamic centralized/decentralized systems would be into chaos when the intertemporal adjustment speed of decision variables is over a threshold. Especially, the intertemporal adjustment speed of greenness degree is more sensitive than the speed of wholesale price and sale price. In the dynamic centralized system, the excessive adjustment speed of greenness degree and sale price will harm the profit of supply chain. In the dynamic decentralized system, the manufacturer should adopt a relatively low value of adjustment speed toward wholesale price.

This paper is organized as follows. Section 2 introduces the notations, assumptions and models. Section 3 derives the static and dynamic equilibrium decisions. Section 4 conducts the numerical simulations to show the complex features of the dynamic dual channel green supply chain. Section 5 provides conclusions.

2 Model Formulation

The paper considers a dual supply chain with one manufacturer and one retailer in a green market where consumers are environmental aware. In the dual channel supply chain, the manufacturer produces a green product featured with greenness degree θ with unit production cost c, and wholesales it to the retailer at wholesale price w. Given the convenience of dual channel, consumers can purchase the product through the online channel operated by the manufacturer at direct sale price p_d or through the offline channel operated by the retailer at retail price p_r.

Based on the facts that consumers are willing to pay higher prices for eco-friendlier products [17], we assume that greenness degree of product is a demand enhancement factor of demand and that the market demand functions are linear with the prices and greenness degree of green product [11]. The demand functions of the retail channel and the direct sale channel are as follows.

$$D_r = \rho\alpha - \beta p_r + \gamma p_d + \tau_r\theta, \tag{1}$$

$$D_d = (1-\rho)\alpha - \beta p_d + \gamma p_r + \tau_d\theta. \tag{2}$$

Where D_r and D_d are the demand for products in the offline channel and the online channel respectively. The subscripts of r and d refer to the retail offline channel and direct online channel respectively. Additionally, the demands are assumed to be deterministic and are equal to the amount quantity sold through the two channels. ρ ($0<\rho<1$) refers to the perception of consumers who prefer offline channel, while $1-\rho$ denote the perception of consumers who prefer the online channel. β is the price sensitivity factor and γ is the cross-price factor, whereas $\beta>\gamma>0$ indicates that the channel's own price has greater influence on the channel demand than the competitive channel's price. τ_r and τ_d are the expansion effectiveness coefficient of the greenness degree per unit of green product in the retail channel and direct sale channel respectively. The differentiation of τ_r and τ_d replies that the different sale channels have different significance on the sales of green product, which indicating the channel compatibility of green product. Similar to Li's work [6], the paper adopts the consistent price policy that the supply channel sets the same offline sale price and online sale price, namely, $p_r = p_d = p$. Thus, the demand functions can be rewritten as follows.

$$D_r = \rho\alpha - \beta p + \tau_r\theta, \tag{3}$$

$$D_d = (1-\rho)\alpha - \beta p + \tau_d\theta. \tag{4}$$

To engage in green product production, the manufacturer has to invest on employing green technologies based on the original production process. Referred to previous work [2], we assume that the greening improvement in the product does not affect the manufacturer's traditional costs of production. Inspired by the fact that firms make initial changes in products and process easily, while the subsequent improvement being more difficult [18], we assume that the cost of greening is a quadratic function of greenness degree $c(\theta) = \eta\theta^2/2$ [15]. η represents the greening investment coefficient. Denote π_r and π_m as the marginal profit of the retailer and the manufacturer. The profit functions of players are as follows.

$$\pi_r = (p-w)D_r, \tag{5}$$

$$\pi_m = (w-c)D_r + (p-c)D_d - c(\theta). \tag{6}$$

3 Equilibrium Solutions

In this section, we derive the optimal pricing and green production strategies in the centralized and decentralized models in a single period. Further, we develop the dynamic centralized and decentralized systems to explore the dynamic characteristics of the proposed dynamic systems by assuming that players are bounded rational.

3.1 Centralized Model

In the centralized model, the manufacturer and the retailer integrate as a whole system that make optimal decisions to maximum whole profit of the supply chain. Denote π_s as the marginal profit of the supply chain. Then, the profit function of the dual supply chain is as follow.

$$\begin{aligned}\pi_s &= \pi_r + \pi_m \\ &= (p-c)(D_r + D_d) - c(\theta)\end{aligned}. \tag{7}$$

3.1.1 Single Period Game Model

Following the two-stage approach [11], we can derive the optimal solution of p and θ. It is easy to approve that π_s is jointly concave to p and θ because that the Hessian matrix of π_s with respect to p and θ is negative defined when $\beta > \frac{(\tau_r + \tau_d)^2}{4\eta}$. In the first stage, we differentiate π_s with respect of p and θ.

$$\frac{\partial \pi_s}{\partial p} = \alpha + \theta(\tau_d + \tau_r) + 2\beta(c - 2p), \tag{8}$$

$$\frac{\partial \pi_s}{\partial \theta} = (p-c)(\tau_r + \tau_d) - \eta\theta. \tag{9}$$

Setting eq. (8)-(9) to zero and solving them simultaneously, we can derive player's optimal decisions as follows. The superscript C refers to the centralized model.

$$p^C = \frac{(\alpha + 2\beta c)\eta - c(\tau_d + \tau_r)^2}{4\beta\eta - (\tau_d + \tau_r)^2}, \tag{10}$$

$$\theta^C = \frac{(\alpha - 2\beta c)(\tau_d + \tau_r)}{4\beta\eta - (\tau_d + \tau_r)^2}. \tag{11}$$

3.1.2 Dynamic Centralized Game Model

In this section, we propose a dynamic centralized system based on the static equilibria derived from single period game model. In fact, decision makers are bounded rational for objective reasons, e.g., the volatile decision-making ability and asymmetric information. Suppose that the decision in next period can be adjusted with bounded rationality, and is based on partial estimation of the marginal profits of the current period, that is, if the marginal profits in period t is positive, the system will raise the price in period $t+1$, which is also suitable for greenness degree. Referred to Bischi' work [18], the dynamic adjustment model can be constructed as follows.

$$\begin{cases} \theta(t+1)=\theta(t)+\delta_1\theta(t)\dfrac{\partial\pi_s}{\partial\theta(t)} \\ p(t+1)=p(t)+\delta_2 p(t)\dfrac{\partial\pi_s}{\partial p(t)} \end{cases} . \tag{12}$$

Where δ_1 and δ_2 are the positive parameters which represent the adjustment speed of decision variable θ and p respectively. What's more, $\dfrac{\partial\pi_s}{\partial p(t)}$ and $\dfrac{\partial\pi_s}{\partial\theta(t)}$ are the marginal benefits at time t which can be obtained from eq. (8)-(9).

An equilibrium point, if it exits, is also a fixed point of the dynamic system (12) [18]. Thus, we can obtain four equilibrium solutions of the system (12) as follows.

$$E_1=(0,0) ,$$
$$E_2=(0,-\frac{c(\tau_c+\tau_d)}{\eta}) ,$$
$$E_3=(\frac{2\beta c+\alpha}{4\beta},0) ,$$
$$E^C=(p^C,\theta^C) .$$

Obviously, E_1, E_2 and E_3 are boundary equilibrium solutions, while E^C is the only equilibrium solution of the dynamic system (12). The Jacobian matrix of system (12) is given by

$$J^C=\begin{pmatrix} 1+\delta_1 f_1 & (\tau_d+\tau_r)\delta_1\theta \\ (\tau_d+\tau_r)\delta_2 p & 1+\delta_2 f_2 \end{pmatrix}. \tag{13}$$

Where $f_1=(p-c)(\tau_d+\tau_r)-2\eta\theta$ and $f_2=(\tau_d+\tau_r)\theta+2\beta(c-4p)+\alpha$.

For equilibrium point E_1, the Jacobian matrix of system (12) is equal to

$$J^C(E_1)=\begin{pmatrix} 1-\delta_1(\tau_d+\tau_r)c & 0 \\ 0 & 1+\delta_2(2\beta c+\alpha) \end{pmatrix}.$$

There are two eigenvalues in $J^C(E_1)$, i.e., $r_1=1-\delta_1(\tau_d+\tau_r)c$ and $r_2=1+\delta_2(2\beta c+\alpha)$. It is easy to prove $|r_2|>1$. So the equilibrium point E_1 is unstable. Similarly, the equilibrium point E_2 and E_3 are unstable. Further, we investigate the stability of E^C by taking the following stability conditions, known as Jury's condition [19]:

$$A:=1+Tr(J^C(E^C))+Det(J^C(E^C))>0 ,$$
$$B:=1-Tr(J^C(E^C))+Det(J^C(E^C)>0 ,$$
$$C:=1-Det(J^C(E^C))>0 .$$

Where $Tr(J^C(E^C))$ and $Det(J^C(E^C))$ are the trace and determinant of $J^C(E^C)$ respectively. The condition above gives a stable region with respect of the adjustment parameters δ_1 and δ_2.

3.2 Decentralized Model

In the decentralized model, the manufacturer and the retailer make decisions to maximize their own profits respectively. We assume that they play a manufacturer-oriented Stackelberg game where the manufacturer determines the wholesale price w and greenness degree θ at first, and then the retailer decides the sale price p based on the manufacturer's decisions later.

3.2.1 Single Period Game Model

Following the two-stage approach, the retailer's response functions toward manufacturer's optimal decisions can be derived by differentiating π_r with respect to p.

$$\frac{\partial}{\partial p}\pi_r = \beta w + \tau_r\theta + (\alpha - 2\beta)\rho . \tag{14}$$

Setting eq. (14) to zero and solving it, we can derive the retailer's best response function.

$$p^*(w,\theta) = \frac{w}{2} + \frac{\tau_r\theta + \rho\alpha}{2\beta} . \tag{15}$$

Substituting eq. (15) into eq. (6), and then differentiating π_m with respect to w and θ, we can obtain:

$$\frac{\partial \pi_m(w,\theta)}{\partial w} = \frac{\tau_d\theta - 3\beta w + 2\beta c + (1-\rho)\alpha}{2} , \tag{16}$$

$$\frac{\partial \pi_m(w,\theta)}{\partial \theta} = \frac{\theta\tau_r^2 - 2\theta\tau_r\tau_d - (\beta w - 2\beta c + \rho\alpha)\tau_d}{2\beta} - \frac{(1-2\rho)\alpha\tau_r - 2\beta\eta\theta}{2\beta} . \tag{17}$$

Setting eq. (16) and (17) into zero simultaneously and solving it, we can derive the manufacturer's optimal decisions. The superscript D refers to the decentralized model.

$$\theta^D = \frac{((1+2\rho)\alpha - 4\beta c)\tau_d + 3(1-2\rho)\alpha\tau_r}{3\tau_r^2 - \tau_d^2 - 6\tau_d\tau_r + 6\beta\eta} , \tag{18}$$

$$w^D = \frac{(\rho\alpha - 2\beta c)\tau_d^2 + ((1-\rho)\alpha + 2\beta c)\tau_r^2 - (\alpha + 4\beta c)\tau_d\tau_r}{(3\tau_r^2 - \tau_d^2 - 6\tau_d\tau_r + 6\beta\eta)\beta} - \frac{2(\rho\alpha - 2\beta c)\eta}{3\tau_r^2 - \tau_d^2 - 6\tau_d\tau_r + 6\beta\eta} . \tag{19}$$

Substituting eq. (18) and (19) into eq. (15), we can obtain the optimal retail price.

3.2.2 Dynamic Decentralized Game Model

In this section, we develop the dynamic decentralized system similar to the dynamic centralized system (12).

$$\begin{cases} \theta(t+1) = \theta(t) + \mu_1\theta(t)\dfrac{\partial \pi_m}{\partial \theta(t)} \\ w(t+1) = w(t) + \mu_2 w(t)\dfrac{\partial \pi_m}{\partial w(t)} \end{cases} . \tag{20}$$

Additionally, the retailer's decision variables directly relate to $w(t)$ and $\theta(t)$.

$$p(t) = \frac{w(t)}{2} + \frac{\tau_r\theta(t) + \rho\alpha}{2\beta} . \tag{21}$$

By applying the same approach applied in subsection 3.1, we can obtain four equilibrium solutions of the dynamic system (20) as follows.

$$E_4 = (0,0) ,$$

$$E_5 = (0, \frac{2\beta c - (1-\rho)\alpha}{3\beta}) ,$$

$$E_6=(\frac{(1-2\rho)\alpha\tau_r+(\rho\alpha-2\beta c)\tau_d}{\tau_r^2-2\tau_r\tau_d+2\beta\eta},0),$$
$$E^D=(\theta^D,w^D).$$

Accordingly, the retail price with regard to the equilibrium points are $p^{E_1}=\frac{\rho\alpha}{2\beta}$, $p^{E_2}=\frac{2\beta c-\alpha+2\rho\alpha}{6\beta}$, $p^{E_3}=\frac{(1-2\rho)\alpha\tau_r+(\rho\alpha-2\beta c)\tau_d\tau_r}{2\beta(\tau_r^2-2\tau_r\tau_d+2\beta\eta)}+\frac{\rho\alpha}{2\beta}$ and $p^{E^D}=p^D$.

Obviously, E_4, E_5 and E_6 are boundary equilibrium solutions, while E^D is the only equilibrium solution of the dynamic decentralized system (20). The Jacobian matrix of system (20) is given by

$$J^D=\begin{pmatrix} 1+\mu_1 f_1 & \frac{1}{2}\mu_2\tau_d\theta \\ \frac{1}{2}\mu_1\tau_d w & 1+\mu_2 f_2 \end{pmatrix}. \qquad \textbf{(22)}$$

Where $f_1=\frac{(4\tau_d\tau_r-2\tau_r^2-4\beta\eta)\theta+\beta\tau_d w+(1-2\rho)\tau_r+(\rho\alpha-2\beta c)\tau_d}{2\beta}$ and $f_2=\frac{\tau_d\theta}{2}-3\beta w+\beta c+\frac{(1-\rho)\alpha}{2}$.

For equilibrium E_4, the Jacobian matrix of system (20) is equal to

$$J^D(E_4)=\begin{pmatrix} 1+\frac{\mu_1}{2\beta}(\alpha\tau_r-2\rho\alpha\tau_r+\rho\alpha\tau_d-2\beta c\tau_d) & 0 \\ 0 & 1+\frac{\mu_2}{2}(2\beta c+(1-\rho)\alpha) \end{pmatrix}.$$

Which gives two eigenvalues, $r_1=1+\frac{\mu_2}{2}(2\beta c+(1-\rho)\alpha)$ and $r_2=1+\frac{\mu_1}{2\beta}(\alpha\tau_r-2\rho\alpha\tau_r+\rho\alpha\tau_d-2\beta c\tau_d)$. It is easy to approve $r_1>1$. So, the equilibrium point E_4 is unstable. Similarly, the equilibrium point E_5 and E_6 are unstable. Then, we investigate the stability of E^D using the following stability conditions [20]:

$$A:=1+Tr(J^D(E^D)+Det(J^D(E^D))>0 \quad ,$$
$$B:=1-Tr(J^D(E^D))+Det(J^D(E^D)>0 \quad ,$$
$$C:=1-Det(J^D(E^D))>0 .$$

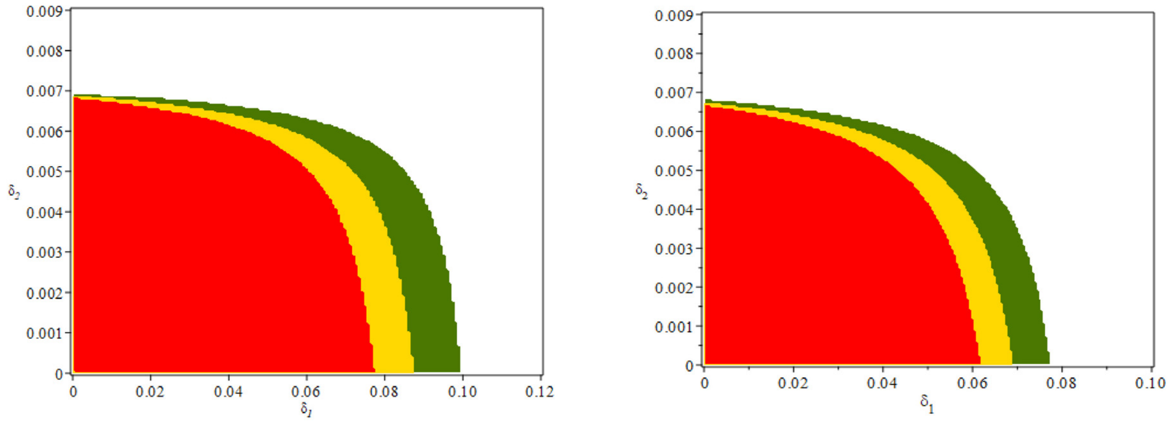
Where $Tr(J^D(E^D))$ and $Det(J^D(E^D))$ are the trace and determinant of $J^D(E^D)$ respectively. The condition gives a stable region in the place of the adjustment parameters μ_1 and μ_2.

4 Numerical Analysis

In this section, numerical simulations are conducted to show the influence of parameters on players' equilibrium solutions. We first choose the fixed values for several parameters based on actual competition. Let $\alpha=200$, $\rho=0.4$, β=4, η=6, $c=10$.

4.1 Dynamical Centralized Model

Fig. 1(a) and Fig. 1(b) show the stable region of the equilibrium point in centralized model with different values of τ_d and τ_r. From Fig. 1(a) where τ_d fixed, i.e., $\tau_d=1$, the areas with red, yellow and green are the stable region with respond to $\tau_r=2.1,1.8,1.5$ respectively. It obviously that the scope of δ_1 is increasing with the decrease of τ_r. Similarly, from Fig. 1(b) where τ_r fixed, i.e., $\tau_r=2$, the stable regions are shown by red, yellow and green with respect to $\tau_d = 1.7, 1.4, 1.1$ respectively. The scope of δ_1 also increases with the decrease of τ_d. When the retail (online) channel compatibility of green product decreases, the range of adjustment speed of greenness degree extends, but the range of adjustment speed of sale price almost remains.

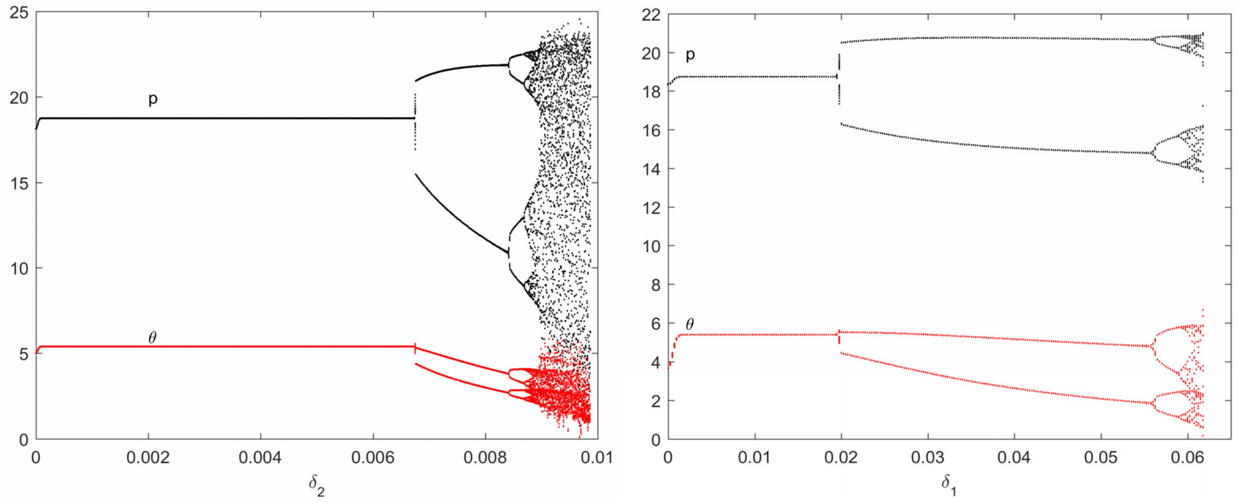


(a) The stable region with $\tau_d = 1$

(b) The stable region with $\tau_r = 2$

Fig. 1. The influence of τ_d and τ_r on the stable region of the system (12)

We set the parameters $\tau_d = 1.7$ and $\tau_r = 2$. Then, the stable equilibrium point in centralized model is $p^C = 18.12$, $\theta^C = 3.65$. When δ_2 is at [0,0.1] and $\delta_1 = 0.01$, the bifurcation diagrams of p and θ are shown in Fig. 2(a). Fig. 2(b) shows the bifurcation diagrams of p and w with $\delta_2 = 0.0065$, and δ_1 varying from 0 to 0.065. From Fig. 2, we can see that p and θ increase slightly with the increment of δ_i at the beginning of the period, and then go to be stable state where the optimal value of sale price and greenness degree are 18.75 and 5.394 respectively. It can be seen that the system is in stable state at first, and then enters into chaos through a series of period doubling bifurcations along with the increase of adjustment parameter δ_i. What's more, the value of δ_1 at the first doubling bifurcation point is apparently greater than δ_2. It implies that the sale price is more sensitive than the greenness degree in the complex dynamic environment.

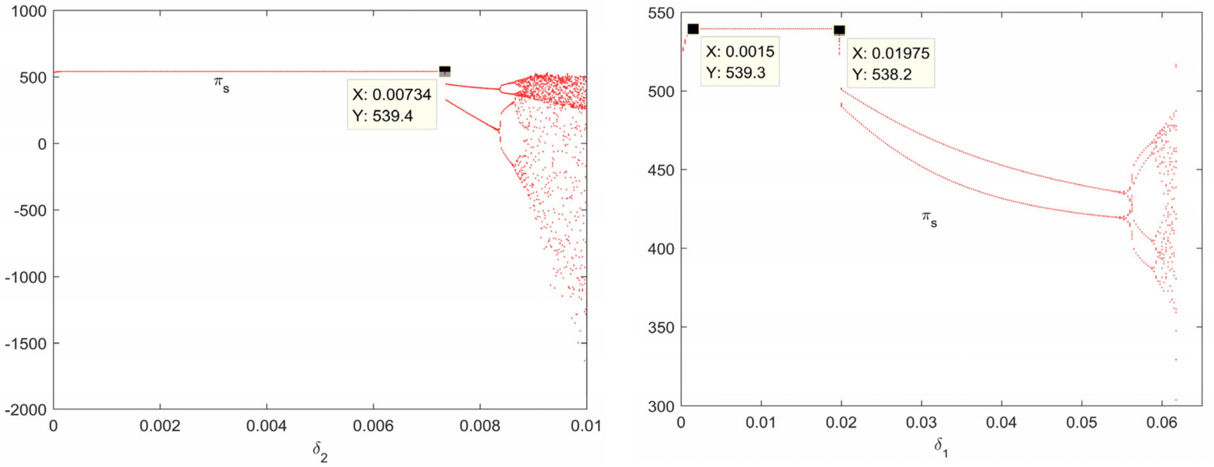


(a) $\delta_1 = 0.01$, δ_2 varying from 0 to 0.01

(b) $\delta_2 = 0.0065$, δ_1 varying from 0 to 0.065

Fig. 2. Bifurcation diagram of the dynamic system (12)

Fig. 3(a) and Fig. 3(b) shows the influences of δ_i on the whole profit of supply chain. In the static state, the adjustment speed of δ_2 has no significance on the profit (shown in Fig. 3(a)), while the whole profit of supply chain increases slightly with the increase of δ_1 at beginning and then goes to stable. When the system enters into bifurcation and chaotic state with the adjustment speed δ_i increase, the whole profit of supply chain fluctuates and it is lower than the profit in the stable state. Thus, a relatively high adjustment speed of greenness degree or sale price is disadvantageous to the dual channel supply chain because the profit of supply chain will be decreased. Similar to the implication from Fig. 2, the profit of the dual channel supply chain is more sensitive with the sale price than the greenness degree. Therefore, the adjustment of sale price should be more cautious.



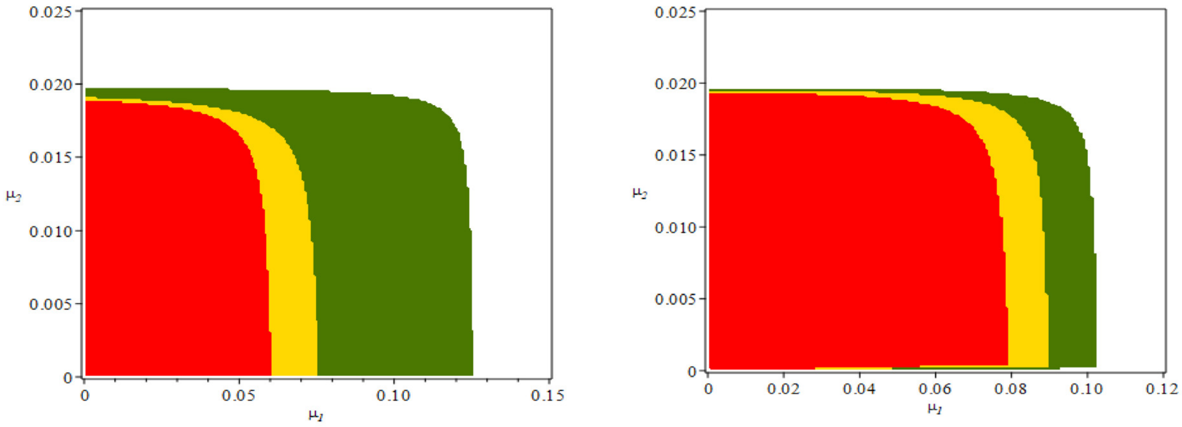
(a) The diagram of supply chain profit with δ_2 varying from 0 to 0.01 when $\delta_1 = 0.01$

(b) The diagram of supply chain profit with δ_1 varying from 0 to 0.065 when $\delta_2 = 0.0065$

Fig. 3. The influence of parameters on supply chain profit

4.2 Dynamical Decentralized Model

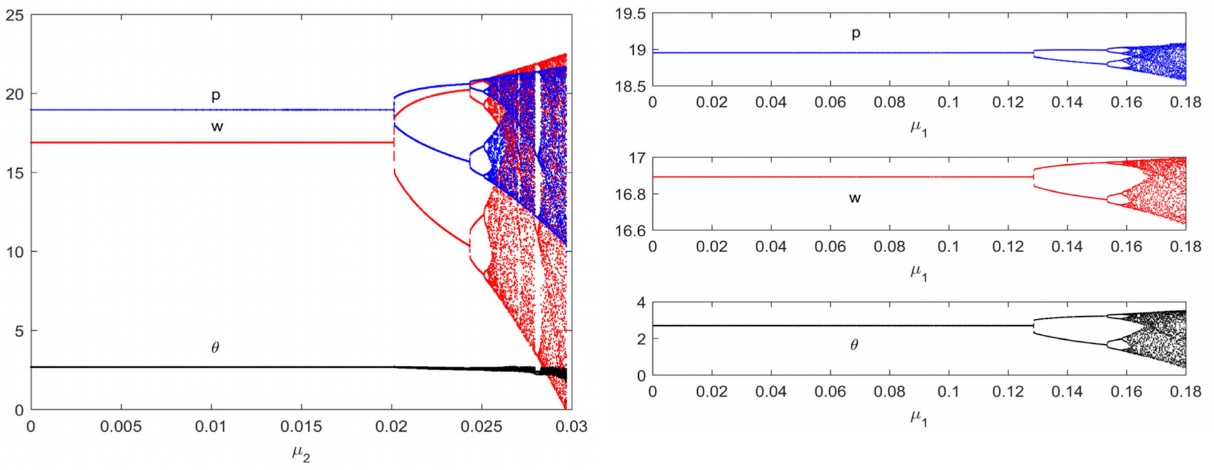
Fig. 4(a) and Fig. 4(b) shows the stable region of the equilibrium point in decentralized model with different values of τ_d and τ_r. From Fig. 4(a) where τ_d fixed, i.e., $\tau_d = 1$, the regions with red, yellow and green are the stable region with respond to $\tau_r = 2.1, 1.8, 1.5$ respectively. It obviously that the scope of μ_1 increases when τ_r decreases. Similarly, from Fig. 4(b) where τ_r fixed, i.e., $\tau_r = 2$, the stable regions are shown by red, yellow and green with respond to $\tau_d = 1.7, 1.4, 1.1$. The scope of μ_1 also increases as τ_d decreases. In the decentralized dual supply chain, when the retail (online) channel compatibility of green product decreases, the range of adjustment speed of greenness degree extends. Different to the centralized scenario, when the retail channel compatibility of green product decreases, the range of adjustment speed of sale price fluctuates. It is reasonable because that the horizontal competition in the decentralized scenario has greater impact on the retailer's optimal strategies.



(a) The stable region $\tau_d = 1$ (b) The stable region $\tau_r = 2$

Fig. 4. The influence of μ_d and μ_r on the stable region of the system (20)

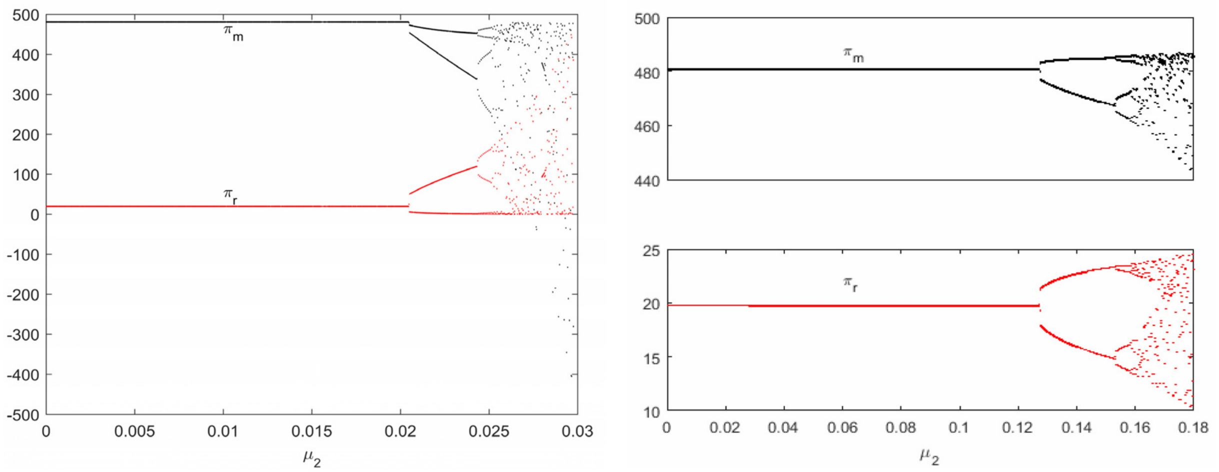
We set the parameters $\tau_d = 1$ and $\tau_r = 1.5$. Then, the equilibrium point in decentralized model is $w^D = 16.89$, $\theta^D = 2.7$. Further, we can calculate the sale price is $p^D = 18.95$. When μ_2 is at [0, 0.03] and $\mu_1 = 0.013$, the bifurcation diagram of p, θ and w is shown in Fig. 5(a). Fig. 5(b) shows the bifurcation diagram of p, θ and w when μ_1 is at [0,0.18] and $\mu_2 = 0.012$. From Fig. 5, we can see that the dynamic system is in stable state at first, and then enters into chaos through a series of period doubling bifurcations along with the increase of adjustment parameters μ_i. Similar to Fig. 2, the value of δ_1 at the first doubling bifurcation point is apparently greater than δ_2. It implies that the sale price is more sensitive than the greenness degree in the complex dynamic environment, which is no matter with the power structure of the dual channel supply chain.



(a) $\mu_1 = 0.013$, μ_2 varying from 0 to 0.03 (b) $\mu_2 = 0.012$, μ_1 varying from 0 to 0.18

Fig. 5. Bifurcation diagram of the dynamic system (20)

Fig. 6(a) and Fig. 6(b) show the influence of μ_i on the manufacturer’s and the retailer’s profit. In the static state, the manufacturer’s and the retailer’s profit are 480.9 and 19.76 respectively. From Fig. 4, we can see that the adjustment speed of μ_i has no influence on the players’ profit in the static state. Similar to dynamic centralized system, the dynamic decentralized system enters into bifurcation and chaotic state with the adjustment speed δ_i increase, and the players' profit fluctuates. Fig. 6(a) indicates that with the increment of μ_2, the manufacturer's profit in chaotic state is lower than in the stable state. However, when the dynamic system enters into chaos state, the effect of μ_2 on retailer's profit and the effect of μ_1 on players' profit cannot predict, which is different to the illustration of Fig. 3. It indicates that the dynamic decentralized system is more complicated than the dynamic centralized system for the horizontal competition within the decentralized dual channel supply chain. Thus, it sensible for the manufacturer to adopt a relatively low μ_2 to avoid the financial losses in the decentralize scenario. What's more, similar to Fig. 3, players' profit are more sensitive with the sale price than the greenness degree, which is indifferent to the power structure of the supply chain.



(a) The diagram of players' profits with μ_2 varying from 0 to 0.03 when $\mu_1 = 0.012$

(b) The diagram of players' profits with μ_1 varying from 0 to 0.18 when $\mu_2 = 0.013$

Fig. 6. The influence of parameters on players' profit

5 Conclusion

The paper investigates the complex features of the dual channel green supply chain in the dynamic setting where green products are considered. The paper obtains the static equilibrium solutions of players under the centralized and decentralized models in the single period at first. Based on static equilibrium solutions, we formulate the dynamic centralized and decentralized systems, derive the dynamic equilibrium solutions and explore the complex features of the dynamic systems by numerical simulation. The results indicate that the adjustment parameters should be kept in a certain range; otherwise, the systems will lose its stability though bifurcations. In the two dynamic models, the players' profits according to adjustment parameters are analyzed. In the dynamic centralized model, the optimal adjustment speed of greenness degree and sale price is beneficial for dual channel green supply chain to enhance the competitiveness. However, excessive adjustment speed of greenness degree and sale price will lead the system into chaos and harm the profit of supply chain. In the dynamic decentralized model, the manufacturer should adopt a relatively low value of adjustment speed toward wholesale price.

The paper investigates the complex feature of the dual channel supply chain under consistent price police. Indeed, it can be extended to inconsistent price police, i.e., the direct sale price and retail price are inconsistent and determined by the manufacturer and retailer respectively. What's more, player's irrational behaviors could be considered, e.g., the player is fair caring instead of profit caring.

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