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Pan Liu (✉ hnycliupan@163.com)

Henan Agricultural University

Feng-jie Zhang

China University of Mining Technology: China University of Mining and Technology

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Pricing strategies of dual-channel green supply chain considering big data information inputs

Pan Liu^{1*}, Feng-jie Zhang^{2**}

- 1 Information & Management College, Henan Agricultural University, NongYe Road 63, Zhengzhou, Henan, China ;
- 2 Scholl of Emergency Management and Safety Engineering, China University of Mining and Technology-Beijing, Beijing

* Correspondence:hnycliupan@163.com

**Correspondence:yczhangfengjie@163.com

Abstract: In the Big Data environment, when green manufacturers invest in the green production technology, to satisfy consumer demand timely and accurately, they may begin to gain consumer performance information (hereafter, CBDI) to design and produce product. However, these will go up their extra costs. Meanwhile, for a green manufacturer who sells the green product through the online channel and the offline channel, the expression of its market demand needs to rethink in the new environment. In these conditions, for a dual-channel green supply chain (hereafter, DGSC), chain members pay more attention on the pricing problems considering the inputs of CBDI and greening R&D. Hence, to resolve this question, a DGSC a green manufacturer selling by the online channel and with one retailer selling by the offline channel was chosen. Afterwards, the demand function of the DGSC was revised, and we analyzed the profits models and its pricing rules in the proposed four common cost-sharing models. Results indicate that whether the retailer bears the CBDI costs or the greening R&D costs, the retailer will not change its retail price. If the retailer can bear some CBDI costs, the alteration tendencies of the best wholesale price are related to the cost-sharing parameter.

Keywords: Big Data information; dual-channel green supply chain; pricing rules; green degree

1 Introduction

In current, the environmental pollution, the global green restrictions and the ascension of consumer environmental awareness all contribute to the increase in the sustainable development awareness of companies. They knew that reducing environmental pollution and producing green product could assist them gain competitive advantages in the future market competition (Zhu & Sarkis, 2006). Thus, many manufacturers or retailers (e.g., Adidas and Appliance World Expo (Li et al., 2016)) began to carry out their green project (Dangelico & Pujari, 2010). Moreover, this project really improved their performance (Rao & Holt, 2005; Jayaram & Avittathur, 2015). Therefore, many companies start to sell green product to protect environment.

However, with the development of Internet and mobile Internet, e-commerce changes more

vigorous and brings the shopping model changes of consumers. In other words, more and more persons begin to shop through online channel. Thus, many enterprises (Dell, IBM, Nike and so on) began to build their online channel (Rahmani & Yavari, 2018). For green manufacturers, many of them have also adopted the online channel and the traditional channel to sell goods. This form is known as a dual-channel green supply chain (DGSC). In fact, the online channel could assist companies to reduce costs and gain new consumers (Chen, Zhang, & Sun, 2012). Thus, adopting dual-channel models is a better option for companies.

With the advent of Big Data, new opportunities have also come for enterprises. For instance, Big Data analysis technology (BDA technology) could assist enterprise to gain consumer performance information (CBDI) timely and accurately (Johanson et al., 2014). Carrying out Big Data plan can assist company to know their supply chain well, thereby, the performance of supply chain can be improved. Of course, gaining market completion advantages, obtaining more earnings and designing new product could also obtain by using Big Data (Jin et al., 2016). Therefore, many enterprises begin to use Big Data. However, for many manufacturers, they face more challenges in collecting and dealing with Big Data. An effective way is data outsourcing, hence, many Big Data information service companies begin to provide the Big Data information service. Based on our investigation, for a green manufacturer, the main information they bought from Big Data information Service Company is the CBDI. Gaining CBDI can assist them to understand consumer well, and then design and produce suitable green products. Meanwhile, it can assist company to set a suitable production batch and lock targeted consumers. However, gaining CBDI also go ups their supernumerary costs. At the same time, the expression of demand formula has also changed.

Therefore, based on the aforementioned analyses, for a green manufacturer who sells product through the online channel and the offline channel, after implementing CBDI, they have some problems needed to solve. 1) For a DGSC, how to describe its demand formula needs to rethink. 2) Considering the inputs of CBDI and product greening R&D, how many cost-sharing models are there? Which are the common models? 3) To gain more profits, how should chain members price in different models? And which models are better for the manufacturer or the retailer?

The essence of these problems is to solve the effects of the inputs of CBDI and the greening R&D on the pricing strategies of a DGSC in different cost-sharing models. For a DGSC, its common cost-sharing patterns with respect to CBDI costs and the green R&D costs include four situations.

1) Both the green manufacturer and the retailer will not bear any costs. 2) The traditional retailer will assist the green manufacturer to bear the CBDI costs. 3) The traditional retailer will assist the green manufacturer to bear the green R&D costs. 4) The traditional retailer will assist the green manufacturer to bear the inputs of the green R&D and the CBDI.

Although pricing rules in green supply chain (GSC), dual-channel supply chain (DSC) and DGSC have been discussed, they appear in the traditional environment. In the Big Data background, pricing issues of a GSC have been also discussed, however, based on a DGSC, the pricing problems is still absent. Hence, in this study, we will attempt to solve it.

The primary dedications: 1) based on a DGSC, we built four profit models according to the proposed cost-sharing models, and then analyzed their pricing rules; 2) the demand formula for a DGSC was refactored to make it suit better in the Big Data era.

The results have some academic values and application values for the choice of cost-sharing model and the pricing decision of DGSC. Theoretically, we revised the demand function of DGSC and proposed four cost-sharing patterns, and then analyzed its pricing strategies thinking about the product green degree level (PGDL) and the CBDI inputs. In reality, for DGSC members, these findings can provide some theoretical guidance in the pricing decision and cost-sharing model choice, and will make chain members implement Big Data plan well.

Fig.1 shows our research roadmap.

2 Literature review

2.1 Pricing rules of DGSC

According to document arrangement, we found that about the problems of pricing strategies in a GSC or a DSC have been widely discussed. For instance, some researchers (Hua et al., 2010; Dan et al., 2012; Huang et al., 2012, and so on) have done efforts in the pricing strategies of a DSC. Based on a GSC, its pricing rules in distinct conditions were also widely discussed (Chen & Sheu, 2009; Zhang et al., 2014; Yang & Xiao, 2017).

Fig. 1. The idea map of this research

However, for a DGSC, its pricing issues' researches are just starting. The related researches are as follows. Song et al. (2018) discussed effects of green degree and fresh degree on performance of a DGSC, moreover, coordination and decision issues were also discussed. Based on a DGSC, Ma et al. (2018) proposed a game method to increase the economic and environmental performance of a DGSC. Barzinpour & Taki (2016) studied the design problems of a DGSC, in this process, and they considered the effects of the prices and other strategies variables on supply chain profits. According to a DGSC, Xu & Zhang (2018) discussed the decision making issues (e.g., pricing rules, profits, and channel choice) of the manufacturer and the retailer in different game models. Considering decentralized and centralized models, Jamali & Rasti-Barzoki (2018) explored the pricing issues and the PGDL and non-green product in a DGSC. Considering the channel environmental sustainability, Chen et al., (2017) explored the pricing rules of a DGSC in decentralized and centralized models. Afterwards, based on a DGSC with one retailer and one manufacturer, Liu (2018) discussed the pricing rules and coordination problems in decentralized and centralized models considering the PGDL. Considering the demand discontinuity, Rahmani & Yavari (2018) explored the pricing strategies of a DGSC with a manufacturer and a retailer. Li et al. (2016) introduced the e-commerce into green supply chain management (GSCM) and discussed the

problems (in other words, pricing policies, channel choice, and coordination) of a DGSC in decentralized and centralized models. Based on the research of Li et al. (2016) and Heydari et al. (2018) investigated the greenness and the prices decisions of a DGSC with a manufacturer, a distributor and a retailer. In their research, the manufacturer determines only the PGDL and the distributor determines the wholesale price. Liu (2019) discussed pricing of a DGSC considering product green degree and channel environment sustainability. Considering demand disruptions, Rahmani & Yavari (2019) discussed the pricing strategies and the green produce decision of a DGSC. Wang et al. (2020) explored the pricing rules of a DGSC with product customization. Meng et al. (2021) analyzed pricing decisions of a DGSC with government subsidies and consumers' dual preferences. Raza & Govindaluri (2019) explored pricing rules in a DGSC with cannibalization and risk aversion. Januardi & Widodo (2021) discussed a DGSC's pricing model by considering uncertainty.

Based on the above analyses, we found that the pricing strategies of a DGSC have been discussed from different angles. However, in the Big Data era, many conditions have changed, thus, its pricing rules should be rethought and explored considering Big Data inputs. To gain this research gap of the DGSC in the Big Data environment, in the next section, we will review the related researches in the Big Data environment.

2.2 Big data appliance in GSCM

In the Big Data era, the applications of Big Data are widely discussed in many areas. In the GSCM area, it is also researched. However, many of these researches focus on applications of BDA method (Quantitative analysis) and concepts of Big Data (Qualitative analysis) in SC (Koot et al., 2020; Lh et al., 2020; Maheshwari et al., 2021; Talwar et al., 2021). Few efforts concentrated on effects of CBDI inputs on decision making in a DGSC.

In the qualitative analysis aspect, many researches explore the usages of Big Data in supply chain sustainability, green application, sustainable manufacturing and so on. For instance, to assist researchers to study the effects of Big Data on supply chain sustainability, Hazen et al. (2016) described eight theories (Actor-network theory, social capital theory, and so on). Song et al. (2016) discussed the methods of environmental performance of supply chain using Big Data, and Wu et al. (2016) described the relationships between Big Data and green application. Dubey (2016) described the role of Big Data in improving the sustainability of world-class manufacturing, and Shah & Wiese

(2018) reviewed the documents about the application of Big Data in sustainable manufacturing. Jeble et al. (2018) discussed the influences of BDA ability on the sustainability of supply chain (social sustainability, economic sustainability, and environmental sustainability). Jiang et al. (2018) discussed the applications of Big Data on the sustainability development in the white spirits area. Bag et al. (2020) valued the role of capability in improving sustainable supply chain performance. Yang et al. (2021) discussed the trust relationship of agri-food supply chain in the big data and blockchain environment. Sundarakani et al. (2021) analyzed the effects of big data and blockchain on a supply chain management in industry 4.0 environment.

In the quantitative analysis aspect, many researches explore the usages of Big Data analytical methods in the sustainable performance evaluation of supply chain, supplier selection, carbon emission optimization, risk control and so on. For instance, based on a Big Data method, Badiezadeh et al. (2018) proposed a Network Data envelopment analysis model to evaluate the performance of sustainable supply chain management (SSCM). Singh et al. (2018) built a new model based on Big Data cloud computing method to assist decision maker to choose a better low carbon supplier in a beef supply chain. By using a BDA method, Zhao et al. (2017) developed a multi-objective optimization model to minimize risk, carbon emission, and the economic cost in a GSC. Papadopoulos et al. (2016) used Big Data and BDA method to describe the elasticity of supply chain for sustainability. For the risks and uncertainties of supply chain caused by the market changes of sustainable development, Wu et al. (2017) collected Big Data from social media and used the fuzzy and grey Delphi method to deal with these data, and then got the relationships between risks and uncertainties. To solve the design issues of sustainable closed-loop supply chain considering multi-uncertainties, Jiao et al. (2018) used Big Data and put forward data-driven methods to go down the uncertainties and greenhouse gas emissions. To solve the location-allocation issue of a multi-stage supply chain with a lowest costs and a highest fill rate, Doolun et al. (2018) put forward “a Data-driven hybrid evolutionary analytical approach”. Zhang et al. (2018) discussed the applications of Big Data in the aspect of energy consumption and emission. To go down the could service cost of Big Data in sustainable companies, Rehman et al. (2016) proposed the concept and a framework of Big Data reduction. Dev et al. (2019) put forward BDA experiments to do real-time interrelated KPI problem of supply chain. Considering the BDA capability, Wang et al. (2020) studied the green supply chain management and firm performance. Chen & Jin (2021) built a big data collaborative

inventory management model for a beer supply chain. Using Big Data, Tian et al. (2021) explored the incentive and supervision mechanism of banks on third-party B2B platforms.

According to the aforementioned analyses, we can get that from the angle of game theory, effects of Big Data or Big Data information inputs on the pricing decisions of a DGSC are very rarely studied. Some related efforts are found, but many shortages were still existence (Yanping et al., 2018; Gawankar et al., 2019; GuoHua & Wei, 2021). For instance, to explore the effects of a Big Data system on the pricing rules of new product and reproduction product, Xu et al. (2019) focused on a manufacturer who sold new product and reproduction product to the same market. However, they did not consider the effects of CBDI inputs on the pricing rules of supply chain. Considering the PGDL and the targeted advertising in the Big Data environment, Liu & Yi (2017) built profit models of four game models and discussed their pricing rules based on a GSC with one retailer and one green manufacturer. They got the relationships among prices, the PGDL and the targeted adverting inputs. Then considering the targeted adverting inputs and the low-carbon emission level, Pan (2019) put forward four cost-sharing patterns and explored their pricing strategies and coordination in the Big Data background. However, they did not discuss the pricing policies of a DGSC considering the PGDL and CBDI. Wang et al. (2021) discussed pricing strategies of a service supply chain considering demand and supply-driven data value and altruistic behavior. Zhang (2020) explored an inventory pricing model of supply chain based on time in the Big Data era. Considering big data marketing and corporate altruistic preferences, Ma et al. (2020) discussed the optimal decisions of a low carbon tourism O2O supply chain. Based on a closed-loop supply chain, Xiang & Xu (2020) discussed the effects of big data marketing, technological innovation and overconfidence on supply chain optimal decisions. Based on C2B e-commerce model and big data technology, Chen (2021) analyzed pricing strategies of mass customization supply chain. Using evolutionary game in the platform service supply chain, Liu et al. (2021) analyzed the governance mechanism of big data discriminatory pricing behavior. Considering the information service based on big data and blockchain, Pan et al. (2020) explored the investment strategies and coordination rules of a green agri-food supply chain. In the next year, Liu (2021) discussed the pricing rules of a green supply chain considering Big Data information inputs in different cost-sharing models.

Based on the literature analyses, we get that previous researches exist some deficiencies: 1) pricing problems of green or low-carbon supply chains have been discussed in the Big Data environment, but based on a DGSC, its pricing rules have not been explored. 2) Pricing rules of a DGSC in the traditional environment have been widely discussed considering different conditions, however, considering the CBDI inputs and the PGDL, and then exploring its pricing issues is failing. 3) Moreover, in the Big Data environment, the expression form of the market demand formula needs to rethink. Therefore, in this paper, effects of the CBDI and the PGDL on the pricing policies of a DGSC will be discussed in different cost-sharing models.

3 Pattern creation and assumption

3.1 Parameters description

c_o shows the unit cost spending in getting CBDI, hereafter, we call it the CBDI costs.

c is the production cost.

g is PGDL, and $g > 0$.

w^i represents the wholesale price, here, $i = \{C, D, OL, OF, O\}$. C stands for the centralized model. D presents that the green manufacturer and the retailer will not bear any costs. OL expresses that the retailer will assist the manufacturer undertake the CBDI costs. OF demonstrates that the retailer will assist the manufacturer to bear the green R&D costs. O shows that the retailer will assist the manufacturer to bear the costs of the green R&D and the CBDI.

η stands for the scale that customers whose data are gathered.

ϖ is the proportion of the target customers after Big Data analysis.

θ is “the industry cost improvement coefficient. By analyzing the external CBDI and the internal information of a company and using it in the company can assist to reduce the company’s cost.” (Liu & Yi, 2017)

D_x stands for the product demand in the x channel, and $x = \{r, m\}$, here, r represents the offline channel and m shows the online channel.

p_x is the retail price in the x channel.

p^i is the retail price in i model.

a shows the basic market demand and is in a certain range.

β_x indicates the ineffective effect of PDGL in the x channel.

π^c is the overall profit of the DGSC.

π_d^i and π_r^i express the profits of the green manufacturer and the retailer in i model, respectively.

3.2 Model description

This research considers a DGSC with a manufacturer selling product through the online channel and a retailer selling product by the offline channel. To protect the environment and improve their market competitiveness, the green manufacturer will invest in greening R&D technology to raise the PGDL. To meet consumers' demand better, the manufacturer should also know their consumers. Gaining the timely and precisely preference information of consumers is an effective way. Big Data provides them an opportunity, but for many traditional manufacturers, getting timely and precisely CDBI is a huge challenge, thus, many of them gaining CDBI from the related CDBI service company. However, in fact, according to our investigation in a publishing firm from Chongqing, China, they produce print-book according to the targeted consumer number from the related CDBI. The collection of consumer data is affected by the number of data points, and the more the arranged data points, the greater the number of consumers whose data is to be collected. Thus, within a limited range of the arranged data points, when the requirement forecast and the produce are according to the CDBI, the forecast threshold value of the market requirement should be definite. If the manufacturer determines the PGDL according to consumer preference CDBI, using the ineffective effect of PGDL can expound the market requirement well. Thus, based on the researches of Liu & Yi (2017), we draw the market demand picture of the two channels considering PGDL (See Fig. 2). Meanwhile, we presume that the market requirement is price-sensitive (Yao & Liu, 2005). Then, the demands in the two channels can be revised as follows:

Fig. 2. Market demand in the two channels considering the PGDL in the Big Data environment

$$D_r = \mu a - \kappa_1 p_r + \kappa_2 p_m - \beta_r g \quad (1)$$

$$D_m = (1 - \mu)a - \kappa_1 p_m + \kappa_2 p_r - \beta_m g \quad (2)$$

In formulas (1) and (2), μ represents the consumer loyalty degree to the offline channel, and $1-\mu$ is the consumer loyalty degree to the online channel, here, $0 \leq \mu \leq 1$. κ_1 expresses the marginal demand of the retail price, and κ_2 stands for the cross-price sensitivity. If $\kappa_1 > \kappa_2$, it demonstrates that the retail price effect of channel is higher than the cross-price effect (Kurata et al., 2007; Mukhopadhyay et al., 2008). $\kappa_1 > \beta_r$ and $\kappa_1 > \beta_m$ indicates that the effects of the retail price in different channel is higher than that of the PGDL.

However, to go down the channel collision, the pricing rule is consistent in the online and offline channels, in other words, the retail prices in the two channels are same (FRUCHTER & TAPIERO, 2005; Cattani et al., 2006). Let $p_r = p_m = p$, thus, the demand formulas can be expressed as follows:

$$D_r = \mu a - \kappa p - \beta_r g \quad (3)$$

$$D_m = (1-\mu)a - \kappa p - \beta_m g \quad (4)$$

Here, $\kappa = \kappa_1 - \kappa_2$.

To enhance the PGDL, the green technical level should be improved, which will go up the related greening R & D investment. According to efforts of Suzumura (1990), the greening R & D costs c_g equals to $zg^2/2$, where, z stands for the greening R & D influence coefficient. The ineffective effect of the same PGDL on consumers in the online channel is higher than that in the offline channel. Because in the offline channel, consumers can examine the green product, in other words, $\beta_r > \beta_m$. Because the market requirement should meet the non-negative constraints, there are $D_i > 0$ and $p > w > \theta c + c_o$.

3.3 Hypothesis

We assume that chain members are completely rational and risk neutral. Meanwhile, the green manufacturer has sufficient manufacturability and outputs only one style goods. Moreover, the sale strategy of the goods is monopolistic. A high PGDL and a low price will be the first choice of consumers. To make products meet consumers demand, the green manufacturer needs to get CBDI.

4 Pricing strategies in the Centralized model and four cost-sharing patterns

In this section, the best pricing strategies of DGSC will be provided in different cost-sharing

models, and the relationships between the best prices of chain members and the related parameters will be analyzed. Then, the comparisons of the best decisions in the DGSC will be done to find which channel is better for chain members.

4.1 The C model

In the C model, considering the CBDI investment and the greening R&D costs, the pricing strategies of DGSC will be discussed. In this model, to maximize the profits of the entire supply chain, chain members are vertically unified and make the prices, the CBDI costs and the greening R&D together. The total profit π^C of the DGSC is

$$\pi^C = (p^C - \theta c - c_o)(D_r + D_m) - \frac{1}{2}zg^2 \quad (5)$$

Proposition 1. If $4\kappa z > (\beta_r + \beta_m)^2$, π^C is a joint concave function about p^C and g . However, in any situations, π^C is not a joint concave function about p^C , c_o and g . (The calculation process saw **Appendix A**.)

Proposition 2. Profits and the retail price of the total supply chain see formulas (6) and (7), respectively. (The calculation process saw **Appendix A**.)

$$(p^{C*}, D^{C*}) = \left(\frac{a - (\beta_m + \beta_r)g + 2\kappa(\theta c + c_o)}{4\kappa}, \frac{a - 2\kappa(\theta c + c_o) - (\beta_m + \beta_r)g}{2} \right) \quad (6)$$

$$\pi^{C*} = \frac{[a - (\beta_r + \beta_m)g - 2\kappa(\theta c - c_o)]^2}{8\kappa} - \frac{zg^2}{2} \quad (7)$$

According to formulas (6) and (7), we got property 1 and the calculation process saw **Appendix A**.

Property 1.

- (1) $\frac{\partial p^{C*}}{\partial g} = -\frac{\beta_m + \beta_r}{4\kappa} < 0$
- (2) $\frac{\partial p^{C*}}{\partial c_o} = \frac{1}{2} > 0$
- (3) $\frac{\partial \pi^{C*}}{\partial g} = \frac{(\beta_m + \beta_r)[2\kappa(\theta c + c_o) + (\beta_m + \beta_r)g - a]}{4\kappa} - zg < 0$
- (4) $\frac{\partial \pi^{C*}}{\partial c_o} = \frac{2\kappa(\theta c + c_o) + (\beta_m + \beta_r)g - a}{2} < 0$

According to (1) and (2) in property 1, we can get that following the ascension of the PGDL, the best retail price in the C model will decrease. Perhaps it is because the usages of greening technologies will make chain members understand their consumers better, and the products they provided can satisfy consumers demand well, then the demand may increase, thereby they can set a

little retail price to get more profits. The changing tendencies are analogous with the investigation of Liu & Yi (2017) and Liu (2021), but their studies are not based on a DGSC. Meanwhile, we discover that with the enhancement of the CBDI inputs, the best retail price in the centralized model will grow. Perhaps it is because the inputs of CBDI add chain members' extra costs, thus, they should set a more retail price to balance these costs. The changing tendencies are analogous with the examination of Liu & Yi (2017), Pan & Yi (2017) and Liu (2021), however, their researches are based on a signal channel supply chain. Moreover, when the costs of CBDI go up one, the best retail price go up 0.5.

According to (3) and (4) in the property 1, we can get that with the ascension of the PGDL and the CBDI costs, the best profits of the entire supply chain in the centralized model will go down. Perhaps it is because that the usages of greening technologies and CBDI make chain members understand their consumers better. The products they provided can satisfy consumers demand well, based on (1) in the property 1, they can set a less retail price to get more earnings.

4.2 The D model

In the D model, chain members will not sharing any costs. Chain members make decision independent to maximize their incomes. Firstly, the green manufacturer determines the wholesale price in the traditional retail channel, the CBDI costs c_o and the PGDL g . Then, the retailer determines the retail price. To gain more profits, cost-sharing model is an effective way.

Earnings of the retailer (π_r^D) and the green manufacturer (π_d^D) are

$$\pi_r^D = (p^D - w^D)D_r^D \quad (8)$$

$$\pi_d^D = (w^D - \theta c - c_o)D_r^D + (p^D - \theta c - c_o)D_d^D - \frac{1}{2}zg^2 \quad (9)$$

Proposition 3. In any conditions, π_r^D is the joint cove function of p^D . If $6z\kappa < 3\beta_r^2 - 6\beta_r\beta_m - \beta_m^2$, $\pi_d^D(w^D, g, c_o)$ is the joint cove function of w^D and g , but it is not the joint cove function of w^D , c_o and g . (The calculation process saw **Appendix B**.)

Based on the aforementioned analyses, we can get that the earnings of chain members have best values. For any g and c_o , proposition 4 provides the best retail price and the best profit in the D model.

Proposition 4. Formulas (11) and (12) present the best retail prices and profits of chain members, respectively. (The calculation process saw **Appendix B**.)

$$(p^{D^*}, w^{D^*}, D_r^{D^*}, D_d^{D^*}) = \left(\frac{(1+2\mu)a - (\beta_m + 3\beta_r)g + 2\kappa(\theta c + c_o)}{6\kappa}, \right. \\ \frac{(1-\mu)a + 2\kappa(\theta c + c_o) - \beta_m g}{3\kappa}, \\ \frac{(4\mu-1)a - 2\kappa(\theta c + c_o) + (\beta_m - 3\beta_r)g}{6}, \\ \left. \frac{-(8\mu-5)a - 2\kappa(\theta c + c_o) - (5\beta_m - 3\beta_r)g}{6} \right) \quad (11)$$

$$(\pi_r^{D^*}, \pi_d^{D^*}) = \left(\frac{M_4^2}{36\kappa}, \right. \\ \left. \frac{M_3 M_4}{18\kappa} - \frac{zg^2}{2} + \frac{M_1 M_2}{36\kappa} \right) \quad (1)$$

2)

Here, $M_1 = -(1+2\mu)a + 4\kappa(\theta c + c_o) + (\beta_m + 3\beta_r)g$, $M_2 = (8\mu-5)a + 2\kappa(\theta c + c_o) + (5\beta_m - 3\beta_r)g$, $M_3 = (\mu-1)a + \beta_m g + \kappa(\theta c + c_o)$, and $M_4 = (1-4\mu)a + 2\kappa(\theta c + c_o) - (\beta_m - 3\beta_r)g$. Because $D_r^{D^*} > 0$ and $D_d^{D^*} > 0$, M_4 and M_2 are lower than zero, and $0.625 > \mu > 0.25$. Then, $M_2 M_1$ and $M_4 M_3$ should be more than zero, therefore, M_3 and M_1 should be lower than zero. Due to $\beta_r > \beta_m$, we get $(\beta_m - 3\beta_r)$ should be lower than zero.

According to formulas (11) and (12), we got property 2 and the calculation process saw **Appendix B**.

Property 2.

- (1) $\frac{\partial p^{D^*}}{\partial g} = -\frac{\beta_m + 3\beta_r}{6\kappa} < 0$, $\frac{\partial w^{D^*}}{\partial g} = -\frac{\beta_m}{3\kappa} < 0$;
- (2) $\frac{\partial p^{D^*}}{\partial c_o} = \frac{1}{3} > 0$, $\frac{\partial w^{D^*}}{\partial c_o} = \frac{2}{3} > 0$;
- (3) $\frac{\partial \pi_r^{D^*}}{\partial g} = \frac{-(\beta_m - 3\beta_r)M_4}{18\kappa} < 0$, $\frac{\partial \pi_d^{D^*}}{\partial g} = \frac{(5\beta_m - 3\beta_r)M_1}{36\kappa} + \frac{(\beta_m - 3\beta_r)M_3}{18\kappa} - gz + \beta_m \frac{M_4}{18\kappa} + \frac{(\beta_m + 3\beta_r)M_2}{36\kappa}$;
- (4) $\frac{\partial \pi_r^{D^*}}{\partial c_o} = \frac{M_4}{9} < 0$, $\frac{\partial \pi_d^{D^*}}{\partial c_o} = \frac{2M_3}{3} < 0$.

According to (1) in the property 2, in the D model, we can get that following the ascent of the PGDL, the best prices of chain members will go down. Perhaps it is because if the manufacturer has implemented the green product plan, it can meet the consumer demand well. Thus, the ineffective effect of PDGL will decrease, and if other parameters are unchanged, the market demand will increase. Therefore, the green manufacturer can provide a little wholesale price, and the retailer can also set a little retail price. These changing tendencies are analogous with the research of Liu & Yi (2017) and Liu (2021). However, they did not discuss these with a DGSC. Moreover, they did not consider the effects of CBDI inputs on pricing strategies of DGSC. In this study, we expanded their research.

Based on (2) in the property 2, in the D model, we discover that with the ascension of CDBI costs, the best retail price and the best wholesale price will increase. Perhaps it is because that the inputs of CDBI go up the manufacturer's extra costs, setting a higher wholesale price can assist it to balance these costs, thereby, the retailer also can set a big retail price. These research efforts are analogous with the study results of Pan & Yi (2017) and Liu (2021). However, their researches are not based on a DGSC, moreover, they did not consider the effects of the PGDL on pricing rules of a DGSC. In addition, about the change of CDBI costs, the wholesale price has a bigger reaction than the best retail price.

From (3) in the property 2, we find that, in the D model, following the ascent of the PGDL, the best profit of the retailer will go down. Perhaps it is because that the implementation of greening R&D go ups the extra costs of the manufacturer, and it will pass this costs to the retailer through setting a high wholesale price. When $1 > \beta_m / \beta_r > 0.6$, the best earnings of the manufacturer will go down with the ascension of the PGDL, in contrast, it is uncertain.

According to (4) in the property 2, we find that, in the D model, with the ascension of CDBI costs, the best profits of the retailer and the manufacturer will go down. Perhaps it is because the CDBI costs will increase the extra inputs of the manufacturer, thus, the manufacturer can provide a high wholesale price, and the retailer can make a big retail price. Thus, earnings of the manufacturer and the retailer will go down. These research results are analogous with the study efforts of Pan & Yi (2017) and Liu (2021). However, their researches were not based on a DGSC, moreover, they did not consider the effects of the PGDL on pricing rules of a DGSC.

4.3 The OL model

In the OL model, the retailer will assist the manufacturer to bear the CDBI cost. Chain members make decision independently to maximize their earnings. Firstly, the green manufacturer determines the wholesale price, the BDI costs c_o and the PGDL g . Then, the retailer determines the retail price. Then, profits of the retailer (π_r^{OL}) and the green manufacturer (π_d^{OL}) are

$$\pi_r^{OL} = (p^{OL} - w^{OL} - \tau c_o) D^{OL} \quad (13)$$

$$\pi_d^{OL} = (w^{OL} - \theta c - (1 - \tau) c_o) D_r^{OL} + (p^{OL} - \theta c - c_o) D_d^{OL} - \frac{1}{2} z g^2 \quad (14)$$

Proposition 5. In any conditions, π_r^{OL} is the joint cove function of p^{OL} . If $6z\kappa < 3\beta_r^2 - 6\beta_r\beta_m - \beta_m^2$, $\pi_d^{OL}(w^{OL}, g, c_o)$ is the joint cove function of w^{OL} and g . When

$\kappa > (2-3\tau)/(3(4-3\tau))$, $\pi_d^{OL}(w^{OL}, g, c_o)$ is the joint cove function of w^{OL} and c_o . But $\pi_d^{OL}(w^{OL}, g, c_o)$ is not the joint cove function of w^{OL} , c_o , and g . (The calculation process saw **Appendix C**.)

Based on the aforementioned analyses, we can get that the earnings of chain members have best values. For any g and c_o , the best prices and the best profits are provided by proposition 6 in the OL model.

Proposition 6. Formulas (16) and (17) offer the best prices and earnings of chain members, respectively. (The calculation process saw **Appendix C**.)

$$(p^{OL*}, w^{OL*}, D_r^{OL*}, D_d^{OL*}) = \left(\frac{(1+2\mu)a - (\beta_m + 3\beta_r)g + 2\kappa(\theta c + c_o)}{6\kappa}, \right. \\ \frac{(1-\mu)a + 2\kappa(\theta c + c_o) - \beta_m g - 3\kappa\tau c_o}{3\kappa}, \\ \frac{(4\mu-1)a - 2\kappa(\theta c + c_o) + (\beta_m - 3\beta_r)g}{6}, \\ \left. \frac{-(8\mu-5)a - 2\kappa(\theta c + c_o) - (5\beta_m - 3\beta_r)g}{6} \right) \quad (16)$$

$$(\pi_r^{OL*}, \pi_d^{OL*}) = \left(\frac{M_4^2}{36\kappa}, \right. \\ \left. \frac{M_3 M_4}{18\kappa} - \frac{zg^2}{2} + \frac{M_1 M_2}{36\kappa} \right) \quad (17)$$

According to formulas (16) and (17), we got property 3 and the calculation process saw **Appendix C**.

Property 3.

- (1) $\frac{\partial p^{OL*}}{\partial g} = -\frac{\beta_m + 3\beta_r}{6\kappa} < 0$, $\frac{\partial w^{OL*}}{\partial g} = -\frac{\beta_m}{3\kappa} < 0$;
- (2) $\frac{\partial p^{OL*}}{\partial c_o} = \frac{1}{3} > 0$, $\frac{\partial w^{OL*}}{\partial c_o} = \frac{2}{3} - \tau$;
- (3) $\frac{\partial \pi_r^{OL*}}{\partial g} = -\frac{(\beta_m - 3\beta_r)M_4}{18\kappa} < 0$, $\frac{\partial \pi_d^{OL*}}{\partial g} = \frac{(5\beta_m - 3\beta_r)M_1}{36\kappa} + \frac{(\beta_m - 3\beta_r)M_3}{18\kappa} - gz + \beta_m \frac{M_4}{18\kappa} + \frac{(\beta_m + 3\beta_r)M_2}{36\kappa}$;
- (4) $\frac{\partial \pi_r^{OL*}}{\partial c_o} = \frac{M_4}{9} < 0$, $\frac{\partial \pi_d^{OL*}}{\partial c_o} = \frac{2M_3}{3} < 0$.

Based on (1) and (2) in properties 2 and 3, with the ascension of the PGDL, prices of chain members in the models of D and OL have a same changing tendencies, in other words, the best prices in the two models will reduce. Namely, bearing the CBDI costs will not change the changing tendencies of prices about the PGDL. Meanwhile, about the change of the PGDL, the changing magnitude of the retail price or the wholesale price in the two modes are same. In addition, with the increase of the CBDI costs, the changing tendencies and magnitudes of the retail prices in the two models are same. However, about the change of the CBDI costs, the changing tendencies of the product wholesale price in the OL model are related to τ . When $\tau > 2/3$, the wholesale price in the

OL model will go up with the jump of the CBDI costs, in contrast, it will go down. These indicate that bearing the CBDI costs will transform the changing tendency of the best wholesale price. But it will not change the transform trend of the best retail price.

According to (3) and (4) in properties 2 and 3, with the ascension of the PGDL, profits of chain members in the models of D and OL have a same changing tendencies, in other words, the retailer's earnings will go down, and when $1 > \beta_m/\beta_r > 0.6$, the best earnings of the manufacturer will go down, in contrast, it is uncertain. Namely, sharing the CBDI costs will not transform the changing tendencies of profits about the PGDL. Meanwhile, about the change of the PGDL, the changing magnitude of the retailer's earnings or the manufacturer's profits in the two modes are same. However, about the change of the CBDI costs, the changing tendencies of the best profits in the two models are same, namely, with the ascension of the CBDI costs, earnings of the chain members will go down. In addition, the changing magnitudes are also same in the two models. These indicate that sharing the CBDI costs will not transform the changing tendencies and magnitudes of the chain members' profits.

4.4 The OF model

In the OF model, the retailer will assist the green manufacturer to bear the green R&D technology costs. Chain members are also independent and make decisions to maximize their earnings. Firstly, the green manufacturer determines the wholesale price, the CBDI costs c_o and the PGDL g . Then, the retailer determines the retail price. Then, profits of the retailer (π_r^{OF}) and the green manufacturer (π_d^{OF}) are

$$\pi_r^{OF} = (p^{OF} - w^{OF})D^{OF} - \psi \frac{1}{2}zg^2 \quad (18)$$

$$\pi_d^{OF} = (w^{OF} - \theta c - c_o)D_r^{OF} + (p^{OF} - \theta c - c_o)D_d^{OF} - (1 - \psi)\frac{1}{2}zg^2 \quad (19)$$

Proposition 7. In any conditions, π_r^{OF} is the joint cove function of p^{OF} . If $6z\kappa(1 - \psi) > 3\beta_r^2 + 6\beta_r\beta_m - \beta_m^2$, $\pi_d^{OF}(w^{OF}, g, c_o)$ is the joint cove function of w^{OF} and g . In any conditions, $\pi_d^{OF}(w^{OF}, g, c_o)$ is not the joint cove function of w^{OF} and c_o . Thus, $\pi_d^{OF}(w^{OF}, g, c_o)$ is not the joint cove function of w^{OF} , c_o and g . (The calculation process saw **Appendix D**.)

Based on the aforementioned analyses, we can get that the earnings of chain members have best values. For any g and c_o , proposition 8 provides the best prices in the OF model.

Proposition 8. Formulas (21) and (22) indicate the best prices and earnings of chain members, respectively. (The calculation process saw **Appendix D**.)

$$(p^{OF*}, w^{OF*}, D_r^{OF*}, D_d^{OF*}) = \left(\frac{(1+2\mu)a - (\beta_m + 3\beta_r)g + 2\kappa(\theta c + c_o)}{6\kappa}, \right. \\ \left. \frac{(1-\mu)a + 2\kappa(\theta c + c_o) - \beta_m g}{3\kappa}, \right. \\ \left. \frac{(4\mu-1)a - 2\kappa(\theta c + c_o) + (\beta_m - 3\beta_r)g}{6}, \right. \\ \left. \frac{-(8\mu-5)a - 2\kappa(\theta c + c_o) - (5\beta_m - 3\beta_r)g}{6} \right) \quad (21)$$

$$(\pi_r^{OF*}, \pi_d^{OF*}) = \left(\frac{M_4^2}{36\kappa} - \frac{\psi z g^2}{2}, \right. \\ \left. \frac{M_3 M_4}{18\kappa} - (1-\psi) \frac{z g^2}{2} + \frac{M_1 M_3}{36\kappa} \right) \quad (22)$$

According to formulas (21) and (22), we got property 4 and the calculation process saw **Appendix D**.

Property 4.

$$(1) \quad \frac{\partial p^{OF*}}{\partial g} = -\frac{\beta_m + 3\beta_r}{6\kappa} < 0, \quad \frac{\partial w^{OF*}}{\partial g} = -\frac{\beta_m}{3\kappa} < 0; \\ (2) \quad \frac{\partial p^{OF*}}{\partial c_o} = \frac{1}{2} > 0, \quad \frac{\partial w^{OF*}}{\partial c_o} = \frac{2}{3}; \\ (3) \quad \frac{\partial \pi_r^{OF*}}{\partial g} = \frac{-(\beta_m - 3\beta_r)M_4}{18\kappa} - \psi z g < 0, \\ \frac{\partial \pi_d^{OF*}}{\partial g} = \frac{(5\beta_m - 3\beta_r)M_1}{36\kappa} - \frac{(\beta_m - 3\beta_r)M_1}{18\kappa} - (1-\psi)gz + \beta_m \frac{M_4}{18\kappa} + \frac{(\beta_m + 3\beta_r)M_2}{36\kappa}; \\ (4) \quad \frac{\partial \pi_r^{OF*}}{\partial c_o} = \frac{M_4}{9} < 0, \quad \frac{\partial \pi_d^{OF*}}{\partial c_o} = \frac{2M_1}{3} < 0.$$

Based on (1) and (2) in properties 2, 4 and 3, with the ascension of the PGDL, prices of chain members in the models of D, OF and OL have a same changing tendencies, in other words, the wholesale price and the retail price in the three models will decrease. Namely, bearing only the greening R&D costs will not transform the changing tendencies of prices with the PGDL. Meanwhile, about the changing of the PGDL, the changing magnitude of the retail price or the wholesale price in the three models are same. In addition, with the increase of the CDBI costs, the changing tendencies and magnitudes of the retail prices or the wholesale prices in the three models are same. These indicate that sharing the CDBI costs will not transform the changing tendencies of the best wholesale price and the best retail price.

According to (3) and (4) in properties 2, 4 and 3, with the ascension of the PGDL, profits of the retailer in the models of D, OF and OL have a same changing tendency, in other words, the

retailer's earnings will go down. The changing tendencies of the manufacturer's profit have a relationship with β_m/β_r . When $1 > \beta_m/\beta_r > 0.6$, following the jump of the PGDL, profits of the green manufacturer will go down. In contrast, we cannot judge its changing tendencies. And the manufacturer's profit is uncertain, namely, sharing only the greening R&D costs will not transform the changing tendencies of the retailer profits about the PGDL. However, about the change of the PGDL, the changing magnitude of the retailer's earnings will change in the OF model, and this change has a relationship with the cost-sharing coefficient ψ . However, about the change of the CBDI costs, the changing tendencies of the best profits in the three models are same, namely, with the ascension of the CBDI costs, earnings of the chain members will go down. Moreover, the change magnitudes are also same in the three models. These indicate that sharing only the greening R&D costs will not transform the changing tendencies of the retailer's, but it will change the manufacturers.

4.5 The O model

In the O model, the retailer will assist the manufacturer to bear the costs of the green R&D technology and the CBDI. Then, profits of the retailer (π_r^O) and the green manufacturer (π_d^O) are

$$\pi_r^O = (p^O - w^O - \tau c_o)D^O - \psi \frac{1}{2}zg^2 \quad (23)$$

$$\pi_d^O = (w^O - \theta c - (1-\tau)c_o)D_r^O + (p^O - \theta c - c_o)D_d^O - (1-\psi)\frac{1}{2}zg^2 \quad (24)$$

Proposition 9. In any conditions, π_r^O is the joint cove function of p^O . If $6z\kappa(1-\psi) > 3\beta_r^2 + 6\beta_r\beta_m - \beta_m^2$, $\pi_d^{OF}(w^{OF}, g, c_o)$ is the joint cove function of w^O and g . In any conditions, $\pi_d^O(w^O, g, c_o)$ is not the joint cove function of w^O and c_o . Thus, $\pi_d^O(w^O, g, c_o)$ is not the joint cove function of w^O , c_o , and g . (The calculation process saw **Appendix E**.)

Based on the aforementioned analyses, we can get that the earnings of chain members have best values. For any g and c_o , proposition 10 provides the best retail price and the best profit in the O model.

Proposition 10. Formulas (26) and (27) shows the best prices and earnings of chain members, respectively. (The calculation process saw **Appendix E**.)

$$(p^{O^*}, w^{O^*}, D_r^{O^*}, D_d^{O^*}) = \left(\frac{(1+2\mu)a - (\beta_m + 3\beta_r)g + 2\kappa(\theta c + c_o)}{6\kappa}, \right. \\ \frac{(1-\mu)a + 2\kappa(\theta c + c_o) - \beta_m g - 3\kappa\tau c_o}{3\kappa}, \\ \frac{(4\mu-1)a - 2\kappa(\theta c + c_o) + (\beta_m - 3\beta_r)g}{6}, \\ \left. \frac{-(8\mu-5)a - 2\kappa(\theta c + c_o) - (5\beta_m - 3\beta_r)g}{6} \right) \quad (26)$$

$$(\pi_r^{O^*}, \pi_d^{O^*}) = \left(\frac{M_4^2}{36\kappa} - \frac{\psi z g^2}{2}, \right. \\ \left. \frac{M_3 M_4}{18\kappa} - (1-\psi) \frac{z g^2}{2} + \frac{M_1 M_2}{36\kappa} \right) \quad (27)$$

According to formulas (26) and (27), we got property 5 and the calculation process saw **Appendix E**.

Property 5.

$$(1) \quad \frac{\partial p^{O^*}}{\partial g} = -\frac{\beta_m + 3\beta_r}{6\kappa} < 0, \quad \frac{\partial w^{O^*}}{\partial g} = -\frac{\beta_m}{3\kappa} < 0; \\ (2) \quad \frac{\partial p^{O^*}}{\partial c_o} = \frac{1}{2} > 0, \quad \frac{\partial w^{OL^*}}{\partial c_o} = \frac{2}{3} - \tau; \\ (3) \quad \frac{\partial \pi_r^{O^*}}{\partial g} = \frac{-(\beta_m - 3\beta_r)M_4}{18\kappa} - \psi z g < 0, \\ \frac{\partial \pi_d^{O^*}}{\partial g} = \frac{(5\beta_m - 3\beta_r)M_1}{36\kappa} - \frac{(\beta_m - 3\beta_r)M_3}{18\kappa} - (1-\psi)gz + \beta_m \frac{M_4}{18\kappa} + \frac{(\beta_m + 3\beta_r)M_2}{36\kappa}; \\ (4) \quad \frac{\partial \pi_r^{O^*}}{\partial c_o} = \frac{M_4}{9} < 0, \quad \frac{\partial \pi_d^{O^*}}{\partial c_o} = \frac{2M_3}{3} < 0.$$

Based on (1) and (2) in properties 2, 3, 4 and 5, with the ascension of the PGDL, prices of chain members in the models of D, OL, OF and O have a same changing tendencies, in other words, the wholesale price and the retail price in the four models will decrease. Namely, sharing the CBDI costs and the greening R&D costs will not change the changing tendencies of the retail prices with the PGDL. Meanwhile, about the change of the PGDL, the changing magnitude of the retail price in the four models are same. In addition, following the increase of the CBDI costs, the changing tendencies and magnitudes of the retail prices in the four models are same. However, about the change of the CBDI costs, the changing tendencies of the wholesale price in the OL model and the O model are same and are related to τ . When $\tau > 2/3$, the wholesale price will go up with the jump of the CBDI costs, in contrast, it will go down. Based on (3) in property 4, sharing only the CBDI costs will transform the changing tendencies of the best wholesale price. But it will not change the transform trend of the best retail price.

According to (3) and (4) in properties 2, 4, 5 and 3, with the ascension of the PGDL, profits of

the retailer in the models of D, OF, O and OL have a same changing tendencies, in other words, the retailer's earnings will go down. The changing tendencies of the manufacturer profit in the O model has a relationship with β_m/β_r . When $1 > \beta_m/\beta_r > 0.6$, following the jump of the PGDL, profits of the green manufacturer will go down. In contrast, we cannot judge its changing tendencies. And the manufacturer's profit is uncertain. Based on (3) in property 4, we get that sharing only the greening R&D costs will not transform the changing tendencies of the retailer profits about the PGDL. However, about the change of the PGDL, the changing magnitude of the retailer's earnings will transform in the O model, and this change has a relationship with the cost-sharing coefficient ψ . However, about the change of the CBDI costs, the changing tendencies of the best profits in the proposed four models are same, namely, with the ascension of the CBDI costs, earnings of the chain members will go down. In addition, the change magnitudes are also same in the proposed four models. These indicate that sharing the greening R&D costs and the CBDI costs will not transform the changing tendencies of the retailer, but it will change the manufacturers'. Meanwhile, it will not transform the changing tendencies of the retail price about the c_o , but it will change the wholesale prices'.

4.6 Cost-sharing model choice

Table 1. Contradistinction of prices and profits in different models

Models	p^*	w^*	π_r^*	π_d^*
D	$\frac{(1+2\mu)a - (\beta_m + 3\beta_r)g + 2\kappa(\theta c + c_o)}{6\kappa}$	$\frac{(1-\mu)a + 2\kappa(\theta c + c_o) - \beta_m g}{3\kappa}$	$\frac{M_4^2}{36\kappa}$	$\frac{M_3 M_4}{18\kappa} - \frac{zg^2}{2} + \frac{M_1 M_2}{36\kappa}$
OL	$\frac{(1+2\mu)a - (\beta_m + 3\beta_r)g + 2\kappa(\theta c + c_o)}{6\kappa}$	$\frac{(1-\mu)a + 2\kappa(\theta c + c_o) - \beta_m g - 3\kappa\tau c_o}{3\kappa}$	$\frac{M_4^2}{36\kappa}$	$\frac{M_3 M_4}{18\kappa} - \frac{zg^2}{2} + \frac{M_1 M_2}{36\kappa}$
OF	$\frac{(1+2\mu)a - (\beta_m + 3\beta_r)g + 2\kappa(\theta c + c_o)}{6\kappa}$	$\frac{(1-\mu)a + 2\kappa(\theta c + c_o) - \beta_m g}{3\kappa}$	$\frac{M_4^2}{36\kappa} - \frac{\psi zg^2}{2}$	$\frac{M_3 M_4}{18\kappa} - (1-\psi)\frac{zg^2}{2} + \frac{M_1 M_2}{36\kappa}$
O	$\frac{(1+2\mu)a - (\beta_m + 3\beta_r)g + 2\kappa(\theta c + c_o)}{6\kappa}$	$\frac{(1-\mu)a + 2\kappa(\theta c + c_o) - \beta_m g - 3\kappa\tau c_o}{3\kappa}$	$\frac{M_4^2}{36\kappa} - \frac{\psi zg^2}{2}$	$\frac{M_3 M_4}{18\kappa} - (1-\psi)\frac{zg^2}{2} + \frac{M_1 M_2}{36\kappa}$
C	$\frac{a - (\beta_m + \beta_r)g + 2\kappa(\theta c + c_o)}{4\kappa}$			$\frac{[a - (\beta_r + \beta_m)g - 2\kappa(\theta c - c_o)]^2}{8\kappa} - \frac{zg^2}{2}$

To compare the prices and profits of chain members in the proposed models, we provide table

1. From table 1, we can get the proposition 11.

Proposition 11. $p^{D*} = p^{OL*} = p^{OF*} = p^{O*} > p^{C*}$, $w^{D*} = w^{OF*} > w^{OL*} = w^{O*}$, $\pi_r^{D*} = \pi_r^{OL*} > \pi_r^{O*} = \pi_r^{OF*}$, and

$$\pi_d^{D^*} = \pi_d^{OL^*} < \pi_d^{O^*} = \pi_d^{OF^*}.$$

Proof. Based on table 1, we can get $p^{D^*} - p^{OL^*} = p^{OF^*} - p^{O^*} = p^{OF^*} - p^{OL^*} = 0$, meanwhile, $p^{OL^*} - p^{C^*} = -M_4/12\kappa > 0$, thus, $p^{D^*} = p^{OL^*} = p^{OF^*} = p^{O^*} > p^{C^*}$. $w^{D^*} - w^{OF^*} = w^{OL^*} - w^{O^*} = 0$, and $w^{OF^*} - w^{OL^*} = \tau c_o$, therefore, $w^{D^*} = w^{OF^*} > w^{OL^*} = w^{O^*}$. Using the analogously method, we get $\pi_r^{D^*} = \pi_r^{OL^*} > \pi_r^{O^*} = \pi_r^{OF^*}$, and $\pi_d^{D^*} = \pi_d^{OL^*} < \pi_d^{O^*} = \pi_d^{OF^*}$. Thus, proposition 11 is proved.

According to proposition 11, we can get that for the retailer, in the models of D and OL, its profit is higher than that in the models of O and OF. Hence, no sharing costs or sharing only the CBDI costs can assist it to gain more earnings. For the green manufacturer, in the models of O and OF, its earnings are higher than that in models of D and OL. Therefore, they should try to make the retailer bear some the greening R&D costs, e.g., providing some the fixed incomes to the retailer or providing a lower wholesale price. Namely, making the DGSC coordinate.

5 Numerical simulation analysis

To explain the proposed properties well, in this section, a numerical simulation case will be provided. Data of this case are from a green manufacturer who has carried out its Big Data plan. And this company is from Zhengzhou, Henan, China. It gains the CBDI from the related Data Company. Then, we choose the data of a best seller as our simulation subject. Let $a=100$, $z=1$, $c=2$, $\kappa=1.5$, $z=1$, $\theta=0.65$. Based on the proposition 4, $0.65 > \mu > 0.25$ and $1 > \beta_m/\beta_r > 0$, we set $\mu=0.4$, $\beta_r=0.6$, $\beta_m=0.4$.

Fig.3 Changing tendencies of decision variables (p^{i*} and w^{i*}) with c_o

Note: In Fig.1 (a), $\tau=0.8$, and in Fig.1 (b), $\tau=0.5$.

Fig.3 demonstrates the relationships between decision variables (p^{i*} and w^{i*}) and the CBDI

costs (c_o). From Fig.3, we can understand that the retail prices in the proposed four cost-sharing patterns will go up with the ascension of the CBDI costs (c_o). Perhaps it is because that the inputs of the CBDI will add the green manufacturer's extra costs, and to balance earnings and expenditures, the green manufacturer should set a high wholesale price or require the retailer to undertake some costs. Thus, the retailer can set a big retail price. Meanwhile, the best retail prices in the proposed four cost-sharing patterns are equal. It indicates whether the retailer bears the CBDI costs or the greening R&D costs, the retailer will not change its retail price. In addition, the retail price in the C model will also go up with the rise of the CBDI costs and is lower than that in the proposed four cost-sharing patterns.

However, the changing tendencies of the wholesale prices in the proposed four cost-sharing patterns have a relationship with the cost-sharing parameter (τ). Based on (a) and (b) in fig.3, we can know that in the D model and the OF model, with the ascension of the CBDI costs (c_o), the wholesale prices will go up. In other words, if the retailer does not bear some costs of the CBDI, the wholesale price and the CBDI costs have a positive relationship. However, if the retailer undertakes some costs of the CBDI costs, relationships between the wholesale price and the CBDI costs are related to the cost-sharing parameter (τ). When $\tau > 2/3$, the wholesale price will decline with the increase of c_o (e.g., Fig.3 (a)). In contrast, the wholesale price will grow with the increase of c_o . The aforementioned analyses show that if the retailer can bear some CBDI costs, the changing tendencies of the best wholesale price are related to the cost-sharing parameter (τ). In summary, (2) in properties 1, 2, 3, 4 and 5 are verified.

Fig.4 Changing tendencies of profits (π_r^{i*} and π_d^{i*}) with c_o

Fig.4 demonstrates the changing tendencies of chain members' earnings with the CBDI costs (c_o). In this picture, $\beta_m/\beta_r = 0.67 > 0.6$. Therefore, according to Fig.4, we get that with the jump of the CBDI costs, earnings of chain members in the proposed four cost-sharing patterns will go down. Perhaps it is because the investments about the CBDI will add the green manufacturer's extra costs, and it will pass to the retailer through the wholesale price, consequently, profits of chain members will go down with the surge of the CBDI costs (c_o). At the same time, if the retailer bears only the CBDI costs (c_o), profits of the retailer and the manufacturer are same with that in the D model, in other words, no cost-sharing condition. However, if the retailer undertakes some costs of the greening R&D, its profits will decline. In other words, bearing the greening R&D costs will go down the retailer earnings. Hence, for the retailer, to gain more profits, it will not bear the greening R&D costs, but it can choose to undertake some CBDI costs. However, if the green manufacturer does not provide advantages, the retailer will not do these. Namely, the DGSC is not coordination. In the next, we will discuss the coordination questions of the DGSC considering the inputs of CBDI. In summary, (4) in properties 1, 2, 3, 4 and 5 are verified.

Fig.5 Changing tendencies of decision variables (p^{i*} and w^{i*}) with g

Fig.5 demonstrates the relationships between decision variables (p^{i*} and w^{i*}) and the PGDL(g). From Fig.5, we can understand that the prices in the proposed four cost-sharing patterns will go down with the ascension of the PGDL(g). Perhaps it is because that the inputs of the greening R&D will make the ineffective effect of PDGL in the two channels go down, thereby, if other parameters are changeless, the market demand will increase (based on the revised market demand in the DGSC). Consequently, the green manufacturer can set a low wholesale price, and for the retailer, it can also set a little retail price. However, the best retail prices are equal in the proposed

four cost-sharing patterns. It shows whether the retailer bears the greening R&D costs or the CBDI costs, the retail price will not change. However, if the retailer has undertaken only some the greening R&D costs, the wholesale price will not change. In addition, the retail price in the centralized model will also go up with the rise of the CBDI costs and is lower than that in the proposed four cost-sharing patterns. In summary, (1) in properties 1, 2, 3, 4 and 5 are verified.

Fig.6 Changing tendencies of profits (π_r^{i*} and π_d^{i*}) with g

Fig.6 demonstrates the changing tendencies of chain members' earnings with the PGDL (g). In this picture, $\beta_m/\beta_r = 0.67 > 0.6$. Therefore, according to Fig.6, we get that following the jump of the PGDL, earnings of chain members in the proposed four cost-sharing patterns will drop. Perhaps it is because that the investment about the greening R&D go ups the green manufacturer's extra costs, and it will pass to the retailer by the wholesale price, consequently, profits of the green manufacturer and the retailer will decline with the surge of the PGDL (g). At the same time, if the retailer bears only the greening R&D costs, profits of chain members are same with that in the D model, in other words, no cost-sharing condition. However, if the retailer undertakes some costs of the greening R&D, its profits will decline. In other words, bearing the greening R&D costs will go down the retailer earnings. Hence, for the retailer, to gain more profits, it will not bear the greening R&D costs. If the green manufacturer wants to the retailer undertake some, it should provide some advantages. Namely, making the DGSC coordinate. In the next, we will discuss the coordination questions of the DGSC considering the inputs of CBDI and greening R&D. In summary, (3) in properties 1, 2, 3, 4 and 5 are verified.

6 Conclusions and significations

Currently, Big Data have been used to gain consumer preference information in green manufacturing industry. Gaining CBDI can assist the manufacturer to produce the green product of consumer demand and help it focus on the targeted consumers. Thus, many green manufacturers have input the CBDI to assist them design and produce product, to balance costs and profits, cost-sharing models are thought to be an effective way. However, in these models, how to price can gain more earnings and which models are good for chain members. These questions are worthy to discuss. Meanwhile, many manufacturers sell their products by the online retail channel and the offline channel. Therefore, in the Big Data environment, exploring the pricing rules of DGSC in different cost-sharing models has an important significations. To explore it, the demand formula is revised considering the PGDL, and a DGSC with one manufacturer selling by the online channel and one retailer selling by the offline channel. Afterwards, in the centralized model and the four cost-sharing patterns, pricing strategies of chain members were discussed. In addition, prices and profits of chain members in the proposed four cost-sharing patterns were compared to gain which model was good for chain members. Findings:

1). The retail prices in the proposed four cost-sharing patterns are equal and will be go up with the ascension of the CBDI costs. Changing tendencies of the wholesale prices in the proposed four cost-sharing patterns have a relationship with the cost-sharing parameter τ .

Namely, whether the retailer bears the CBDI costs or the greening R&D costs, the retailer will not change its retail price. If the retailer can bear some CBDI costs, the changing tendencies of the best wholesale price are related to the cost-sharing parameter.

2). With the jump of the CBDI costs, earnings of chain members in the proposed four cost-sharing patterns will go down. If the retailer bears only the CBDI costs (c_o), profits of chain members are same with that in the D model.

3). The retail prices and the wholesale prices in the proposed four cost-sharing patterns will decrease with the ascension of the PGDL. Whether the retailer bears the greening R&D costs or the CBDI costs, the retail price will not change. However, if the retailer has undertaken only some the greening R&D costs, the wholesale price will not transform. In addition, the retail price in the C model will also increase with the rise of the CBDI costs and is lower than that in the proposed four

cost-sharing patterns.

4). When $1 > \beta_m / \beta_r > 0.6$, following the jump of the PGDL, earnings of chain members in the proposed four cost-sharing patterns will drop. If the retailer undertakes some costs of the greening R&D, its profits will decline, but profits of the manufacturer will go up.

5) For the manufacturer, making the retailer bear the greening R&D costs has advantages. It can choose the OF model or the O model. However, for the retailer, bearing the greening R&D costs will not go up its profits, thus, it can choose the D model or the OL model.

This research has some academic values and application values in the pricing decisions and the cost-sharing model choices of DGSC. Theoretically, to make the demand function suit well in the Big Data environment, we revised the demand function of DGSC. Meanwhile, we proposed four cost-sharing patterns and analyzed its pricing strategies considering the PGDL and the CBDI inputs. These enrich the pricing theory of DGSC in the Big Data environment. In reality, for DGSC members, these findings can provide some theoretical guidance in the pricing decisions and the cost-sharing model choices, and will make chain members implement Big Data plan well.

However, because of the limitations of paper length and personal ability, there are some shortages in this research. For instance, we have proved that in the proposed four cost-sharing patterns, chain members do not reach a coordinated state. However, we don't discuss the methods to make chain members coordinate. In the future, we will explore the coordination conditions in the proposed four cost-sharing patterns, and assist members to gain more profits. In addition, we suppose that chain members are risk-neutral and completely rational (in fact, these are the usual assumptions to simplify calculation), in essence, chain members have a certain risk appetite. Hence, in the next stage, we can relax these hypotheses.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this paper.

Human and animal rights This article does not contain any studies with human participants or animals performed by any of the authors.

Appendix A.

Calculation process of Proposition 1.

Proof. Based on formulas (3), (4) and (5), solving the second-order partial derivative of π^C about p^C , g and c_o , we can get the matrix H . From H , we discovered $\frac{\partial^2 \pi^C}{\partial (p^C)^2} = -4\kappa < 0$, $\frac{\partial^2 \pi^C}{\partial (g)^2} = -z < 0$, $\frac{\partial^2 \pi^C}{\partial (p^C)^2} \frac{\partial^2 \pi^C}{\partial (g)^2} - (\frac{\partial^2 \pi^C}{\partial p^C \partial g} \frac{\partial^2 \pi^C}{\partial g \partial p^C})^2 = 4\kappa z - (\beta_m + \beta_r)^2 > 0$, thus, π^C is the joint cove function about p^C and g . But $\frac{\partial^2 \pi^C}{\partial (c_o)^2} \frac{\partial^2 \pi^C}{\partial (g)^2} - (\frac{\partial^2 \pi^C}{\partial c_o \partial g} \frac{\partial^2 \pi^C}{\partial g \partial c_o})^2 = -(\beta_m + \beta_r)^2 < 0$, therefore, π^C is not the joint cove function about p^C , c_o and g .

$$H = \begin{bmatrix} \frac{\partial^2 \pi^C}{\partial (p^C)^2} & \frac{\partial^2 \pi^C}{\partial p^C \partial g} & \frac{\partial^2 \pi^C}{\partial p^C \partial c_o} \\ \frac{\partial^2 \pi^C}{\partial g \partial p^C} & \frac{\partial^2 \pi^C}{\partial (g)^2} & \frac{\partial^2 \pi^C}{\partial g \partial c_o} \\ \frac{\partial^2 \pi^C}{\partial c_o \partial p^C} & \frac{\partial^2 \pi^C}{\partial c_o \partial g} & \frac{\partial^2 \pi^C}{\partial (c_o)^2} \end{bmatrix} = \begin{bmatrix} -4\kappa & -(\beta_r + \beta_m) & 2\kappa \\ -(\beta_r + \beta_m) & -z & \beta_r + \beta_m \\ 2\kappa & \beta_r + \beta_m & 0 \end{bmatrix}$$

Based on proposition 1, we can get that the earnings of the total supply chain has best values. For any g and c_o , proposition 2 provides the best retail price and the best profit in the centralized model.

Calculation process of Proposition 2.

Proof. Based on formulas (3), (4) and (5), solving the first-order partial derivative of π^C about p^C , and let it equal to zero, in other words, $\partial \pi^C / \partial p^C = 0$. Then, we can get p^{C*} , and putting p^{C*} into formulas (3) and (4), the best order quantity D^{C*} can be got. Based on these, the best earnings of the whole supply chain was got. In summary, Proposition 2 was confirmed.

Calculation process of Property 1.

According to formulas (6) and (7), we can get $\partial p^{C*} / \partial g = -\frac{\beta_m + \beta_r}{4\kappa}$ and $\partial p^{C*} / \partial c_o = -1/2 < 0$, because $\beta_m + \beta_r > 0$ and $\kappa > 0$, $\partial p^{C*} / \partial g > 0$. $\partial \pi^{C*} / \partial g = \frac{(\beta_m + \beta_r)[2\kappa(\theta c + c_o) + (\beta_m + \beta_r)g - a]}{4\kappa} - zg$ and $\partial \pi^{C*} / \partial c_o = [2\kappa(\theta c + c_o) + (\beta_m + \beta_r)g - a] / 2$. Because $D^{C*} = [a - 2\kappa(\theta c + c_o) - (\beta_m + \beta_r)g] / 2 > 0$,

$\partial \pi^{c*} / \partial g < 0$ and $\partial \pi^c / \partial c_o < 0$. In summary, Property 1 is proved.

Appendix B.

Calculation process of Proposition 3.

Proof. Solving the second order partial derivative of π_r^D with p^D , we get $\frac{\partial^2 \pi_r^D}{\partial (p^D)^2} = -2\kappa < 0$,

thus, π_r^D is the joint cove function of p^D . Solving the first order partial derivative of π_r^D with

p^D , and let $\frac{\partial \pi_r^D}{\partial p^D} = 0$, we get formula (10).

$$p^D(w^D) = \frac{\mu a - \beta_r g + \kappa w^D}{2\kappa} \quad (10)$$

Putting $p^D(w^D)$ into formula (9), we get $\pi_d^D(w^D, g, c_o)$. Based on $\pi_d^D(w^D, g, c_o)$, solving the second-

order partial derivative of $\pi_d^D(w^D, g, c_o)$ about w^D , g and c_o , we can get the matrix H^D . From

$$H^D, \quad \text{we discovered} \quad \frac{\partial^2 \pi_d^D}{\partial (w^D)^2} = -3\kappa/2 < 0, \quad \frac{\partial^2 \pi_d^D}{\partial (g)^2} = \frac{\beta_r(2\beta_m - \beta_r)}{2\kappa} - z < 0,$$

$$\frac{\partial^2 \pi_d^D}{\partial (w^D)^2} \frac{\partial^2 \pi_d^D}{\partial (g)^2} - \left(\frac{\partial^2 \pi_d^D}{\partial w^D \partial g} \right)^2 = -\frac{3\beta_r(2\beta_m - \beta_r)}{4} + \frac{3\kappa z}{2} - \frac{(\beta_m)^2}{2} > 0, \text{ therefore, } \pi_d^D \text{ is the joint cove}$$

function about p^D and g . However, $\frac{\partial^2 \pi_d^D}{\partial (c_o)^2} \frac{\partial^2 \pi_d^D}{\partial (g)^2} - \left(\frac{\partial^2 \pi_d^D}{\partial c_o \partial g} \right)^2 = -(\beta_m)^2 < 0$, thus, π_d^D is not

the joint cove function about w^D , c_o and g .

$$H^D = \begin{bmatrix} \frac{\partial^2 \pi_d^D}{\partial (w^D)^2} & \frac{\partial^2 \pi_d^D}{\partial w^D \partial g} & \frac{\partial^2 \pi_d^D}{\partial w^D \partial c_o} \\ \frac{\partial^2 \pi_d^D}{\partial g \partial w^D} & \frac{\partial^2 \pi_d^D}{\partial (g)^2} & \frac{\partial^2 \pi_d^D}{\partial g \partial c_o} \\ \frac{\partial^2 \pi_d^D}{\partial c_o \partial w^D} & \frac{\partial^2 \pi_d^D}{\partial c_o \partial g} & \frac{\partial^2 \pi_d^D}{\partial (c_o)^2} \end{bmatrix} = \begin{bmatrix} \frac{-3\kappa}{2} & \frac{-\beta_m}{2} & \kappa \\ \frac{-\beta_m}{2} & \frac{\beta_r(2\beta_m - \beta_r)}{2\kappa} - z & \beta_m \\ \kappa & \beta_m & 0 \end{bmatrix}$$

Calculation process of Proposition 4.

Proof. Based on formulas (3), (4), (8) and (9), solving the first-order partial derivative of π_r^D

about p^D , and let it equal to zero, in other words, $\partial \pi_r^D / \partial p^D = 0$. Then, we can get $p^D(w^D)$, and

putting $p^D(w^D)$ into formulas (9), we get the best wholesale price

$$w^{D*} = [(1 - \mu)a + 2\kappa(\theta c + c_o) - \beta_m g] / 3\kappa. \text{ Then the best retail price and the best order quantity } D_r^{D*}$$

and D_d^{D*} can be got. Based on these, the best earnings of chain members were got. In summary,

proposition 4 was confirmed.

Calculation process of Property 2.

According to formulas (11) and (12), we can get $\frac{\partial p^{D^*}}{\partial g} = -\frac{\beta_m + 3\beta_r}{4\kappa} < 0$, $\frac{\partial w^{D^*}}{\partial g} = -\frac{\beta_m}{3\kappa} < 0$, $\frac{\partial p^{D^*}}{\partial c_o} = \frac{1}{3} > 0$, and $\frac{\partial w^{D^*}}{\partial c_o} = \frac{2}{3} > 0$. $\frac{\partial \pi_r^{D^*}}{\partial g} = \frac{-(\beta_m - 3\beta_r)M_4}{18\kappa}$, because $M_4 < 0$ and $(\beta_m - 3\beta_r) < 0$, $\frac{\partial \pi_r^{D^*}}{\partial g} < 0$. $\frac{\partial \pi_d^{D^*}}{\partial g} = \frac{(5\beta_m - 3\beta_r)M_1}{36\kappa} + \frac{(\beta_m - 3\beta_r)M_3}{18\kappa} - gz + \beta_m \frac{M_4}{18\kappa} + \frac{(\beta_m + 3\beta_r)M_2}{36\kappa}$, because $M_4 < 0$, $M_3 < 0$, $M_2 < 0$, $M_1 < 0$ and $(\beta_m - 3\beta_r) < 0$, $\frac{\partial \pi_d^{D^*}}{\partial g}$ is not sure. Meanwhile, we get $\frac{\partial \pi_r^{D^*}}{\partial c_o} = \frac{M_4}{9} < 0$ and $\frac{\partial \pi_d^{D^*}}{\partial c_o} = \frac{2M_3}{3} < 0$. In summary, Property 2 is confirmed.

Appendix C.

Calculation process of Proposition 5.

Proof. Solving the second order partial derivative of π_r^{OL} with p^{OL} , we get

$\frac{\partial^2 \pi_r^{OL}}{\partial (p^{OL})^2} = -2\kappa < 0$, thus, π_r^{OL} is the joint cove function of p^{OL} . Solving the first order partial

derivative of π_r^{OL} with p^{OL} , and let $\frac{\partial \pi_r^{OL}}{\partial p^{OL}} = 0$, we get formula (15).

$$p^{OL}(w^{OL}) = \frac{\mu a - \beta_r g + \kappa(w^{OL} + \tau c_o)}{2\kappa} \quad (15)$$

Putting $p^{OL}(w^{OL})$ into formula (14), we get $\pi_d^{OL}(w^{OL}, g, c_o)$. Based on $\pi_d^{OL}(w^{OL}, g, c_o)$, solving the second-order partial derivative of $\pi_d^{OL}(w^{OL}, g, c_o)$ about w^{OL} , g and c_o , we can get the matrix

H^{OL} . From H^{OL} , we discovered $\frac{\partial^2 \pi_d^{OL}}{\partial (w^{OL})^2} = -3\kappa/2 < 0$, $\frac{\partial^2 \pi_d^{OL}}{\partial (g)^2} = \frac{\beta_r(2\beta_m - \beta_r)}{2\kappa} - z < 0$,

$\frac{\partial^2 \pi_d^{OL}}{\partial (w^{OL})^2} \frac{\partial^2 \pi_d^{OL}}{\partial (g)^2} - (\frac{\partial^2 \pi_d^{OL}}{\partial w^{OL} \partial g} \frac{\partial^2 \pi_d^{OL}}{\partial g \partial w^{OL}})^2 = -\frac{3\beta_r(2\beta_m - \beta_r)}{4} + \frac{3\kappa z}{2} - \frac{(\beta_m)^2}{4}$. If $-\frac{3\beta_r(2\beta_m - \beta_r)}{4} + \frac{3\kappa z}{2} - \frac{(\beta_m)^2}{4} > 0$, in

other words, $6z\kappa < 3\beta_r^2 - 6\beta_r\beta_m - \beta_m^2$, π_d^{OL} is the joint cove function about w^{OL} and g .

$\frac{\partial^2 \pi_d^{OL}}{\partial (w^{OL})^2} \frac{\partial^2 \pi_d^{OL}}{\partial (c_o)^2} - (\frac{\partial^2 \pi_d^{OL}}{\partial w^{OL} \partial c_o} \frac{\partial^2 \pi_d^{OL}}{\partial c_o \partial w^{OL}})^2 = \frac{-3\kappa^2\tau(4-3\tau) - \kappa(2-3\tau)}{4}$, if $-3\kappa^2\tau(4-3\tau) - \kappa(2-3\tau) > 0$, in other

words, $\kappa > (2-3\tau)/(3(4-3\tau))$, $\pi_d^{OL}(w^{OL}, g, c_o)$ is the joint cove function of w^{OL} and c_o . However,

$\frac{\partial^2 \pi_d^{OL}}{\partial (c_o)^2} \frac{\partial^2 \pi_d^{OL}}{\partial (g)^2} - (\frac{\partial^2 \pi_d^{OL}}{\partial c_o \partial g} \frac{\partial^2 \pi_d^{OL}}{\partial g \partial c_o})^2 = [\frac{\beta_r(2\beta_m - \beta_r)}{2\kappa} - z] \frac{\kappa\tau(4-3\tau)}{2} - \frac{(2-\tau)^2}{4}$, the positive and negative signs of

it cannot be judged. Thus, π_d^{OL} is not the joint cove function about w^{OL} , c_o and g .

$$H^{OL} = \begin{bmatrix} \frac{\partial^2 \pi_d^{OL}}{\partial (w^{OL})^2} & \frac{\partial^2 \pi_d^{OL}}{\partial w^{OL} \partial g} & \frac{\partial^2 \pi_d^{OL}}{\partial w^{OL} \partial c_o} \\ \frac{\partial^2 \pi_d^{OL}}{\partial g \partial w^{OL}} & \frac{\partial^2 \pi_d^{OL}}{\partial (g)^2} & \frac{\partial^2 \pi_d^{OL}}{\partial g \partial c_o} \\ \frac{\partial^2 \pi_d^{OL}}{\partial c_o \partial w^{OL}} & \frac{\partial^2 \pi_d^{OL}}{\partial c_o \partial g} & \frac{\partial^2 \pi_d^{OL}}{\partial (c_o)^2} \end{bmatrix} = \begin{bmatrix} \frac{-3\kappa}{2} & \frac{-\beta_m}{2} & \frac{\kappa(2-3\tau)}{2} \\ \frac{-\beta_m}{2} & \frac{\beta_r(2\beta_m - \beta_r)}{2\kappa} - z & \frac{2-\tau}{2} \\ \frac{\kappa(2-3\tau)}{2} & \frac{2-\tau}{2} & \frac{\kappa\tau(4-3\tau)}{2} \end{bmatrix}$$

Calculation process of Proposition 6.

Proof. Based on formulas (3), (4), (13) and (14), solving the first-order partial derivative of π_r^{OL} about p^{OL} , and let it equal to zero, in other words, $\partial\pi_r^{OL}/\partial p^{OL} = 0$. Then, we can get $p^{OL}(w^{OL})$, and putting $p^{OL}(w^{OL})$ into formulas (14), we get the best wholesale price $w^{OL*} = [(1-\mu)a + 2\kappa(\theta c + c_o) - \beta_m g - 3\kappa\tau c_o]/3\kappa$. Then the best retail price and the best order quantity D_r^{OL*} and D_d^{OL*} can be got. Based on these, the best earnings of chain members were got. In summary, proposition 6 was confirmed.

Calculation process of Property 3.

According to formulas (16) and (17), we can get $\frac{\partial p^{OL*}}{\partial g} = -\frac{\beta_m + 3\beta_r}{4\kappa} < 0$, $\frac{\partial w^{OL*}}{\partial g} = -\frac{\beta_m}{3\kappa} < 0$, $\frac{\partial p^{OL*}}{\partial c_o} = \frac{1}{3} > 0$, and $\frac{\partial w^{OL*}}{\partial c_o} = \frac{2}{3} - \tau$. $\frac{\partial \pi_r^{OL*}}{\partial g} = \frac{-(\beta_m - 3\beta_r)M_4}{18\kappa}$, because $M_4 < 0$ and $(\beta_m - 3\beta_r) > 0$, $\frac{\partial \pi_r^{OL*}}{\partial g} < 0$. $\frac{\partial \pi_d^{OL*}}{\partial g} = \frac{(5\beta_m - 3\beta_r)M_1}{36\kappa} + \frac{(\beta_m - 3\beta_r)M_3}{18\kappa} - gz + \beta_m \frac{M_4}{18\kappa} + \frac{(\beta_m + 3\beta_r)M_2}{36\kappa}$, because $M_4 < 0$, $M_3 < 0$, $M_2 < 0$, $M_1 < 0$ and $(\beta_m - 3\beta_r) < 0$, $\frac{\partial \pi_d^{OL*}}{\partial g}$ is not sure. Meanwhile, we get $\frac{\partial \pi_r^{OL*}}{\partial c_o} = \frac{M_4}{9} < 0$ and $\frac{\partial \pi_d^{OL*}}{\partial c_o} = \frac{2M_3}{3} < 0$. In summary, Property 3 is confirmed.

Appendix D.

Calculation process of Proposition 7.

Proof. Solving the second order partial derivative of π_r^{OF} with p^{OF} , we get $\frac{\partial^2 \pi_r^{OF}}{\partial (p^{OF})^2} = -2\kappa < 0$, thus, π_r^{OF} is the joint cove function of p^{OF} . Solving the first order partial derivative of π_r^{OF} with p^{OF} , and let $\frac{\partial \pi_r^{OF}}{\partial p^{OF}} = 0$, we get formula (20).

$$p^{OF}(w^{OF}) = \frac{\mu a - \beta_r g + \kappa w^{OF}}{2\kappa} \quad (20)$$

Putting $p^{OF}(w^{OF})$ into formula (19), we get $\pi_d^{OF}(w^{OF}, g, c_o)$. Based on $\pi_d^{OF}(w^{OF}, g, c_o)$, solving the second-order partial derivative of $\pi_d^{OF}(w^{OF}, g, c_o)$ about w^{OF} , g and c_o , we can get the matrix H^{OF} . From H^{OF} , we discovered $\frac{\partial^2 \pi_d^{OF}}{\partial (w^{OF})^2} = -3\kappa/2 < 0$, $\frac{\partial^2 \pi_d^{OF}}{\partial (g)^2} = \frac{\beta_r(2\beta_m - \beta_r)}{2\kappa} - z(1-\psi) < 0$, $\frac{\partial^2 \pi_d^{OF}}{\partial (w^{OF})^2} \frac{\partial^2 \pi_d^{OF}}{\partial (g)^2} - (\frac{\partial^2 \pi_d^{OF}}{\partial w^{OF} \partial g} \frac{\partial^2 \pi_d^{OF}}{\partial g \partial w^{OF}})^2 = -\frac{3\beta_r(2\beta_m - \beta_r)}{4} + \frac{3\kappa z(1-\psi)}{2} - \frac{(\beta_m)^2}{4}$. If $-\frac{3\beta_r(2\beta_m - \beta_r)}{4} + \frac{3\kappa z(1-\psi)}{2} - \frac{(\beta_m)^2}{4} > 0$, in other words, $6z\kappa(1-\psi) > \beta_r^2 + 6\beta_r\beta_m - \beta_m^2$, π_d^{OF} is the joint

cove function about w^{OF} and g . Due to $\partial^2 \pi_d^{OF} / \partial (c_o)^2 = 0$, $\pi_d^{OF}(w^{OF}, g, c_o)$ is not the joint cove function of w^{OF} and c_o . Thus, π_d^{OF} is not the joint cove function about w^{OF} , c_o and g .

$$H^{OF} = \begin{bmatrix} \frac{\partial^2 \pi_d^{OF}}{\partial (w^{OF})^2} & \frac{\partial^2 \pi_d^{OF}}{\partial w^{OF} \partial g} & \frac{\partial^2 \pi_d^{OF}}{\partial w^{OF} \partial c_o} \\ \frac{\partial^2 \pi_d^{OF}}{\partial g \partial w^{OF}} & \frac{\partial^2 \pi_d^{OF}}{\partial (g)^2} & \frac{\partial^2 \pi_d^{OF}}{\partial g \partial c_o} \\ \frac{\partial^2 \pi_d^{OF}}{\partial c_o \partial w^{OF}} & \frac{\partial^2 \pi_d^{OF}}{\partial c_o \partial g} & \frac{\partial^2 \pi_d^{OF}}{\partial (c_o)^2} \end{bmatrix} = \begin{bmatrix} \frac{-3\kappa}{2} & \frac{-\beta_m}{2} & \kappa \\ \frac{-\beta_m}{2} & \frac{\beta_r(2\beta_m - \beta_r)}{2\kappa} - z(1-\psi) & \beta_m \\ \kappa & \beta_m & 0 \end{bmatrix}$$

Calculation process of Proposition 8.

Proof. Based on formulas (3), (4), (18) and (19), solving the first-order partial derivative of π_r^{OF} about p^{OF} , and let it equal to zero, in other words, $\partial \pi_r^{OF} / \partial p^{OF} = 0$. Then, we can get $p^{OF}(w^{OF})$, and putting $p^{OF}(w^{OF})$ into formulas (19), we get the best wholesale price $w^{OF*} = [(1-\mu)a + 2\kappa(\theta c + c_o) - \beta_m g] / 3\kappa$. Then the best retail price and the best order quantity D_r^{OF*} and D_d^{OF*} can be got. Based on these, the best earnings of chain members were got. In summary, proposition 8 was confirmed.

Calculation process of Property 4.

According to formulas (21) and (22), we can get $\frac{\partial p^{OF*}}{\partial g} = -\frac{\beta_m + 3\beta_r}{6\kappa} < 0$, $\frac{\partial w^{OF*}}{\partial g} = -\frac{\beta_m}{3\kappa} < 0$, $\frac{\partial p^{OF*}}{\partial c_o} = \frac{1}{2} > 0$, and $\frac{\partial w^{OF*}}{\partial c_o} = \frac{2}{3}$. $\frac{\partial \pi_r^{OF*}}{\partial g} = \frac{-(\beta_m - 3\beta_r)M_4 - \psi z g}{18\kappa}$, because $M_4 < 0$ and $(\beta_m - 3\beta_r) > 0$, $\frac{\partial \pi_r^{OF*}}{\partial g}$ is lower than zero. $\frac{\partial \pi_d^{OL*}}{\partial g} = \frac{(5\beta_m - 3\beta_r)M_1}{36\kappa} + \frac{(\beta_m - 3\beta_r)M_3}{18\kappa} - gz + \beta_m \frac{M_4}{18\kappa} + \frac{(\beta_m + 3\beta_r)M_2}{36\kappa}$, because $M_4 < 0$, $M_3 < 0$, $M_2 < 0$, $M_1 < 0$ and $(\beta_m - 3\beta_r) < 0$, when $1 > \beta_m / \beta_r > 0.6$, $\frac{\partial \pi_d^{OL*}}{\partial g} < 0$. Meanwhile, we get $\frac{\partial \pi_r^{OF*}}{\partial c_o} = \frac{M_4}{9} < 0$ and $\frac{\partial \pi_d^{OF*}}{\partial c_o} = \frac{2M_3}{3} < 0$. In summary, Property 4 is confirmed.

Appendix E.

Calculation process of Proposition 9.

Proof. Solving the second order partial derivative of π_r^O with p^O , we get $\frac{\partial^2 \pi_r^O}{\partial (p^O)^2} = -2\kappa < 0$, thus, π_r^O is the joint cove function of p^O . Solving the first order partial derivative of π_r^O with p^O , and let $\frac{\partial \pi_r^O}{\partial p^O} = 0$, we get formula (25).

$$p^O(w^O) = \frac{\mu a - \beta_r g + \kappa w^O}{2\kappa} \quad (25)$$

Putting $p^o(w^o)$ into formula (19), we get $\pi_d^o(w^o, g, c_o)$. Based on $\pi_d^o(w^o, g, c_o)$, solving the second-order partial derivative of $\pi_d^o(w^o, g, c_o)$ about w^o , g and c_o , we can get the matrix H^o . From H^o , we discovered $\frac{\partial^2 \pi_d^o}{\partial (w^o)^2} = -3\kappa/2 < 0$, $\frac{\partial^2 \pi_d^o}{\partial (g)^2} = \frac{\beta_r(2\beta_m - \beta_r)}{2\kappa} - z(1-\psi) < 0$, $\frac{\partial^2 \pi_d^o}{\partial (w^o)^2} \frac{\partial^2 \pi_d^o}{\partial (g)^2} - (\frac{\partial^2 \pi_d^o}{\partial w^o \partial g} \frac{\partial^2 \pi_d^o}{\partial g \partial w^o})^2 = -\frac{3\beta_r(2\beta_m - \beta_r)}{4} + \frac{3\kappa z(1-\psi)}{2} - \frac{(\beta_m)^2}{4}$. If $-\frac{3\beta_r(2\beta_m - \beta_r)}{4} + \frac{3\kappa z(1-\psi)}{2} - \frac{(\beta_m)^2}{4} > 0$, in other words, $6z\kappa(1-\psi) < 3\beta_r^2 + 6\beta_r\beta_m - \beta_m^2$, π_d^o is the joint cove function about w^o and g . Due to $\partial^2 \pi_d^o / \partial (c_o) = -\kappa\tau(\frac{3\kappa}{2} - 2) > 0$, $\pi_d^o(w^o, g, c_o)$ is not the joint cove function of w^o and c_o . Thus, π_d^o is not the joint cove function about w^o , c_o and g .

$$H^o = \begin{bmatrix} \frac{\partial^2 \pi_d^o}{\partial (w^o)^2} & \frac{\partial^2 \pi_d^o}{\partial w^o \partial g} & \frac{\partial^2 \pi_d^o}{\partial w^o \partial c_o} \\ \frac{\partial^2 \pi_d^o}{\partial g \partial w^o} & \frac{\partial^2 \pi_d^o}{\partial (g)^2} & \frac{\partial^2 \pi_d^o}{\partial g \partial c_o} \\ \frac{\partial^2 \pi_d^o}{\partial c_o \partial w^o} & \frac{\partial^2 \pi_d^o}{\partial c_o \partial g} & \frac{\partial^2 \pi_d^o}{\partial (c_o)^2} \end{bmatrix} = \begin{bmatrix} \frac{-3\kappa}{2} & \frac{-\beta_m}{2} & \frac{\kappa(2-3\tau)}{2} \\ \frac{-\beta_m}{2} & \frac{\beta_r(2\beta_m - \beta_r)}{2\kappa} - z(1-\psi) & \frac{(\beta_r - \beta_m)(2-\tau)}{2} \\ \frac{\kappa(2-3\tau)}{2} & \frac{(\beta_r - \beta_m)(2-\tau)}{2} & -\kappa\tau(\frac{3\kappa}{2} - 2) \end{bmatrix}$$

Calculation process of Proposition 10.

Proof. Based on formulas (3), (4), (23) and (24), solving the first-order partial derivative of π_r^o about p^o , and let it equal to zero, in other words, $\partial \pi_r^o / \partial p^o = 0$. Then, we can get $p^o(w^o)$, and putting $p^o(w^o)$ into formulas (24), we get the best wholesale price $w^{o*} = [(1-\mu)a + 2\kappa(\theta c + c_o) - \beta_m g - 3\kappa\tau c_o] / 3\kappa$. Then the best retail price and the best order quantity D_r^{o*} and D_d^{o*} can be got. Based on these, the best earnings of chain members were got. In summary, proposition 10 was confirmed.

Calculation process of Property 5.

According to formulas (26) and (27), we can get $\frac{\partial p^{o*}}{\partial g} = -\frac{\beta_m + 3\beta_r}{6\kappa} < 0$, $\frac{\partial w^{o*}}{\partial g} = -\frac{\beta_m}{3\kappa} < 0$, $\frac{\partial p^{o*}}{\partial c_o} = \frac{1}{2} > 0$, and $\frac{\partial w^{o*}}{\partial c_o} = \frac{2}{3} - \tau$. $\frac{\partial \pi_r^{o*}}{\partial g} = \frac{-(\beta_m - 3\beta_r)M_4}{18\kappa} - \psi z g$, because $M_4 < 0$ and $(\beta_m - 3\beta_r) > 0$, $\frac{\partial \pi_r^{o*}}{\partial g}$ is lower than zero. $\frac{\partial \pi_d^{o*}}{\partial g} = \frac{(5\beta_m - 3\beta_r)M_1}{36\kappa} + \frac{(\beta_m - 3\beta_r)M_3}{18\kappa} - gz + \beta_m \frac{M_4}{18\kappa} + \frac{(\beta_m + 3\beta_r)M_2}{36\kappa}$, because $M_4 < 0$, $M_3 < 0$, $M_2 < 0$, $M_1 < 0$ and $(\beta_m - 3\beta_r) < 0$, when $1 > \beta_m / \beta_r > 0.6$, $\frac{\partial \pi_d^{o*}}{\partial g} < 0$. Meanwhile, we get $\frac{\partial \pi_r^{o*}}{\partial c_o} = \frac{M_4}{9} < 0$ and $\frac{\partial \pi_d^{o*}}{\partial c_o} = \frac{2M_3}{3} < 0$. In summary, property 5 is confirmed.

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