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Product Greenness and Pricing Strategy of Supply Chain Incorporating Asymmetric Heterogeneous Preferences

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ABSTRACT The decision making of product greenness and pricing strategy is important to achieve sustainable competitiveness of supply chain systems. Behavioral studies find that individual preferences, such as altruism and fairness, can affect the decision and performance of the supply chain significantly. However, the previous widely adopted assumption contradicts the private, asymmetric, and diverse behaviors in reality. This paper considers a green supply chain with asymmetric heterogeneous preferences, in which the manufacturer does not know whether the behavioral type of the retailer is self-interest or altruistic. The optimal decisions on product greenness and pricing strategy of the supply chain under asymmetric heterogeneous preferences are obtained with a game analytic model of incomplete information. The impact of asymmetric preferences on product greenness, price, and supply chain performance is attained by comparing the results under symmetric and asymmetric scenarios. How heterogeneous preferences change the impact of asymmetric preferences is presented with sensitivity analysis. The case study illustrates and verifies the impact of asymmetric preferences, and its sensitivity with respect to heterogeneous preferences. The findings show that asymmetric preferences will reduce the product greenness and wholesale price decided by the manufacturer, will enhance the retail price decided by the self-interest retailer, and meanwhile reduce that decided by the altruistic retailer. Moreover, asymmetric preferences will decrease the manufacturer's profit, reduce the self-interest retailer's profit, and enhance the altruistic retailer's profit while reducing the altruistic retailer's utility. Their influence extents will increase in the heterogeneity of preferences with few exceptions in cases of the self-interest retailer's profit and the altruistic retailer's utility. The theoretical findings generate some managerial implications, by which for example it is necessary to adjust promptly the estimation about the behavior types of supply chain partners.

INDEX TERMS Supply chain, asymmetric heterogeneous preferences, product greenness, pricing strategy.

I. INTRODUCTION

Sustainable development balancing economic, environmental, and social performance, is the basic mission of World Commission on Environment and Development (WCED) and the core goal of the 2030 Agenda for Sustainable Development arranged by United Nations. At United Nations Climate Action Summit held in New York 2019, a report released by the World Meteorological Organization (WMO) documents the increasing threats to social development and ecosystems. In order to reduce emissions to net zero by 2050, countries, firms, non-profit organizations, and customers should work collaboratively. Public environmental awareness has spread widely, an increasing number of customers are willing to purchase green products and pay more for higher greenness. For manufacturers, the enhancement of product greenness is not only the external requirement of sustainable development and environmental regulation, but also an internal important tool to achieve stable competitiveness. Lenovo, one of the largest world manufacturers of PC, engaged in research and

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development of new green technology to reduce emissions, and coordinated with its supply chain partners to enhance product greenness. Many famous firms such as Carrefour, Coca Cola, Colgate Palmolive, Unilever, MARS, Apple, and Barilla, co-signed the New Plastics Economy Global Commitment Spring 2019 Report, and agreed to take actions to reduce plastic packaging, and launch delivery models of reuse. Haier, a famous manufacturer of household appliance in China, has been adopting new green technology to reduce energy consumption, which includes the total process of green design, green manufacture, green maintenance and green recycling.

The decision making of both product greenness and price is very important for supply chains to achieve sustainable competitive advantage. Greener products require higher prices because firms have to spend additional costs to reduce emissions. High product greenness with low prices can't balance the budget, whereas low product greenness with high prices can't attract customers. As an important academic topic, the product greenness and pricing strategy of the supply chain has attracted numerous attentions. For example, Liu and Chen [1], Zhang and Liu [2], and Rahmani and Yavari [3] explored the joint decision of product greenness and pricing strategy in dyadic, triple, and dual supply chain respectively, whereas Ghosh and Shah [4], Madani and Rasti-Barzoki [5], and Yuan *et al.* [6] investigated how various drivers such as power structure and government intervention influenced the product greenness and profitability of the supply chain.

Additionally, a number of behavioral literature found that the decision making of product greenness and price will be heavily impacted by behavioral preferences such as fairness, and altruism. For example, how the behavioral preferences except traditional self-interest affect the decision making and operational performance of the supply chain has been examined widely [7]–[11]. Specifically, few studies which concerned the product greenness and pricing strategy incorporating behavioral preferences, had found that it was possible for altruistic preference to improve product greenness of a cooperative supply chain [12], whereas also possible for fairness preference to reduce product greenness in a green e-commerce supply chain [13].

However, previous literature always assumed that the behavioral types of supply chain members were public and symmetric. For example, the retailer in Caliskan-Demirag *et al.* [7] and Wang *et al.* [13] was assumed to concern with distributional fairness and the manufacturer surely knew the downstream of the supply chain was a fairness type retailer, but the retailer in Lin [10] and Hui *et al.* [12] was assumed to be altruistic and the manufacturer knew the downstream was an altruistic type retailer, and that in Su *et al.* [11] was assumed to be publicly known reciprocal type. As a matter of fact, such an assumption also implicitly means homogeneous preferences, by which the retailer must behave in the same single way, and thereby the manufacturer definitely knows the behavioral type of the retailer. It deals with each type of behavioral preferences separately, and thereby easily attains the product greenness and pricing strategy by assuming symmetric information of preferences, which contradicts with the reality of diverse behavioral types because firms behave in various ways. Actually, the retailer is of multiple types, including fairness, altruistic, reciprocal type, and so on, which is defined as heterogeneous preferences. Furthermore, the information of behavioral types is asymmetric, which is defined as asymmetric preferences. It is impossible for the manufacturer to surely know the concrete type of the retailer. Generally speaking, the behavioral types of supply chain members are heterogeneous, private, and asymmetric, instead of homogeneous, public, and symmetric, adopted in previous literature. The decision making of product greenness and price under public symmetric preferences discussed in previous literature may be actually irrational and should been modified. Aiming at the contradiction, this paper probes the product greenness and pricing strategy of supply chain under asymmetric heterogeneous preferences, to answer following important questions and provide managerial implications:

(1) What is the optimal product greenness and pricing strategy of supply chain? It reveals the method, process, and results of decision making in scenario of asymmetric heterogeneous preferences.
(2) What is the impact of asymmetric preferences? Namely, how will the product greenness, price, and supply chain performance be affected by asymmetric preferences? It explains the reason why incorporating asymmetric preferences.
(3) What is the sensitivity with respect to heterogeneous preferences? That is to say, how will heterogeneous preferences change the above impact of asymmetric preferences? It describes the extent of necessity to incorporate asymmetric heterogeneous preferences.

To answer those questions, a supply chain consisting of a manufacturer and a retailer is analyzed. The behavioral type of the manufacturer is self-interest, which is symmetric information. The behavioral type of the retailer is diverse, either self-interest or altruistic, which is private asymmetric information. The manufacturer does not know the concrete type of the retailer, and hence has to decide the product greenness and wholesale price with the goal of maximizing expected profits in the approach of Harsanyi doctrine. The self-interest retailer knows that the upstream is a self-interest manufacturer, and decides the self-interest retail price to maximize profit. The altruistic retailer also knows that the manufacturer is self-interest, and decides the altruistic retail price to maximize utility instead of profit. By using method of game theory with incomplete information, the optimal decision of product greenness and price is obtained. The impact of asymmetric preferences on product greenness, price, and supply chain performance is analyzed, which is described as the difference between those under asymmetric and symmetric preferences. The sensitivity with respect to heterogeneous preferences is attained, which is represented by the change of the above difference with respect to the heterogeneity of preferences.

This paper makes four primary contributions as follows.

First, it incorporates originally asymmetric heterogeneous preferences into the decision making of product greenness and pricing strategy in supply chains, and thereby makes more realistic decision models. However, previous literature always adopted the unreasonable assumption of public symmetric behavioral types, which should be improved.

Second, it obtains the impact of asymmetric preferences on product greenness, price, and supply chain performance. However, previous literature has hardly touched this point because it has always been exploring a symmetric scenario of behavioral types.

Third, it attains analytically the sensitivity with respect to heterogeneous preferences by describing how the impact of asymmetric preferences on product greenness, price, and supply chain performance will been changed respectively by heterogeneous preferences. However, previous literature has never reached before because it has always been adopting the assumption of the single same type.

Finally, it makes a real case study and provides vital results, where actual data obtained from BAIC Motor are employed to explore the law of decision making in the entire supply chain system. However, previous literature usually carried out numerical analysis with unreal data, which may result in some impractical and irrational suggestions to firms and government.

The remainder of this paper is organized into seven sections. Section 2 reviews the literature, the framework and assumptions are configured in Section 3. The optimal product greenness and price is attained in Section 4. Section 5 analyzes the impact of asymmetric preferences on product greenness, price, and supply chain performance, and its sensitivity with respect to heterogeneous preferences is probed in Section 6. Section 7 provides a case study, and conclusions are presented in Section 8.

II. LITERATURE REVIEW

The topic of the above key questions is related to product greenness, pricing strategy, and behavioral preferences in the supply chain. The following reviews the relevant literature in three streams.

A. PRODUCT GREENNESS OF SUPPLY CHAIN

With wide spread of public environmental awareness, more and more customers are willing to buy green products even with a high premium [14]. Consequently, an increasing number of manufacturers implemented green investment to enhance the product greenness and competitiveness [15]. The decision making of product greenness in various situations have been explored deeply.

Regarding cooperative mechanism, Zhang and Liu [2] attained the optimal greenness of a triple supply chain, found that both revenue-sharing contract and Nash negotiation mechanism could positively incentivize cooperation in enhancing greenness; Song and Gao [16] shown that the greening level and profitability of supply chain could be improved by a revenue-sharing contract, and specifically, the bargaining revenue-sharing contract promoted both greening level and overall profit higher than the revenue-sharing contract led by the retailer; Gao and Zhang [17] investigated the interaction of green degree and sales effort, and revealed that the relative coefficients had positive influences on the green degree and sales effort.

Regarding dual-channel, Zhang *et al.* [18] investigated the greening strategies with cross-channel return service, and found that the retailer would cooperate with the manufacturer when the spillover effect was greater than a threshold by comparing results with those without cross-channel return service; Heydari *et al.* [19] obtained the optimal decision on product greenness of the manufacturer, e-channel price of the distributor, and retail price of the retailer, and developed a coordinated decision model to enhance greenness and reduce price in both the e-channel and retail channel.

Regarding power structures, Ghosh and Shah [4] analyzed how channel structures affected greening levels, prices, and profits; Dey *et al.* [20] investigated the impact of power structures and their interaction with strategic inventory on the marginal-cost-intensive green product, and revealed that dynamic planning could result in exemplary outcomes of product greenness; Lou *et al.* [21] found that the channel leader was not necessarily more profitable than the follower, and when the green practice difficulty of the leader was less than a certain threshold, ceding partial dominant power to the follower may benefit both sides.

Regarding governmental intervention, Yuan *et al.* [6] analyzed the impact of different governmental subsidy strategies on the product greenness level, selling effort, manufacturer's profit, and retailer's profit, shown that the government subsidy could increase product greenness and retailer's selling effort; Chen and Akmalul'Ulya [22] revealed that the reward-penalty mechanism designed by the government could improve the return rate and green effort of the manufacturer; Saha *et al.* [23] compared the effectiveness of consumer subsidy and manufacturer subsidy in a three stage framework under green-marketing effort sharing contracts, and found that manufacturer subsidy could lead to higher product greenness; and Nielsen *et al.* [24] compared the government incentives of single and two-period green supply chain shown that product greenness reached the maximum level under governmental policy on total investment in R&D.

From the above discussion, it is clear that how to decide the optimal product greenness of the supply chain is an important academic topic about environmental protection and sustainable development, and thereby has been paid much attention. With the integration of behavioral economics and supply chain management, the optimal decision making of product greenness under behavioral preferences will become an important issue in line with academic and practical development. Actually, a few began to analyze the influence of behavioral preferences on product greenness. For example, altruistic preferences could improve the product greenness of a cooperative supply chain [12] and the decision making and operational efficiency of a low-carbon e-commerce closed-loop supply chain [25], whereas fairness concerns could reduce the product greenness in a green e-commerce supply chain [13]. But, the influence of asymmetric heterogeneous preferences has never been touched. Therefore, this paper will explore the optimal product greenness of the supply chain under asymmetric heterogeneous preferences.

B. PRICING STRATEGY OF SUPPLY CHAIN

As one of the basic core issues in the decision making of the supply chain, pricing strategy has been attracting heavy academic attentions. Usually, the decision of price is joint with others.

Regarding joint decision with replenishment strategy, in a supply chain consisting of a supplier and many competing retailers, Bernstein and Federgruen [26] investigated how the supplier chose the wholesale price, and then how each retailer chose independently their individual retail price in combination with a replenishment strategy as the response to the decision of wholesale price.

Regarding joint decision with service and quality effort, Chen *et al.* [27] presented an analytical framework of the decision making of retailer's service, manufacturer's service, and quality effort, and analyzed how the customer loyalty to the direct channel affected the above service and quality effort; Li *et al.* [28] revealed that the showrooming effect would enhance the wholesale price decided by the manufacturer in a dual-channel supply chain.

Regarding joint decision with product greenness, which is related to the topic of this paper directly, Chen and Zhou [29] probed the optimal pricing and green strategies of a dynamic decentralized supply chain with the competitive or supportive retail service, and shown that initial green perception of consumers determined whether the skimming pricing strategy or penetration pricing strategy was adopted; Mondal and Giri [30] investigated the strategies of pricing, green innovation, marketing effort, and recycling, and found that integrating pricing and green innovation could improve supply chain performance; Madani and Rasti-Barzoki [5] constructed a wide framework, where the government behaved as the leader to decide governmental financial interventions, and a competitive green and a non-green supply chain behaved as the followers to decide green degree and prices, and analyzed how the pricing strategy interacted with the green degree and governmental financial interventions.

Clearly, the joint decision of product greenness and pricing strategy is a common but important topic in the supply chain. As many experimental and empirical findings in behavioral economics have shown behavioral preferences would change results significantly, a few attentions paid to how behavioral preferences affect the joint decision of product greenness and pricing strategy and their interactions in the supply chain. For example, altruistic preference could reduce the product price, enhance the product greenness [12], and thereby improve the firms' profit [10]; furthermore, it also could change the pricing strategy of a dual-channel environmental hotel supply chain, and made that the online travel agent model was more profitable than the merchant model [31]. But, asymmetric heterogeneous preferences have never been incorporated into the joint decision of product greenness and pricing strategy. Consequently, to follow the trend of academic and practical development, this paper will explore the joint decision making of product greenness and pricing strategy of the supply chain under asymmetric heterogeneous preferences.

C. BEHAVIORAL PREFERENCES IN SUPPLY CHAIN

A lot of behavioral studies have accumulated sufficient evidence that firms don't always behave in a pure self-interest way, although traditional economics treats it as a basic assumption [32]. Behavioral preferences such as fairness, reciprocity, and altruism, have important impacts on decision making and operational performance of the supply chain [9], [33]. With the development of the behavioral supply chain, how various preferences except the traditional self-interest affect the decision making and operational performance of the supply chain has been examined widely.

Regarding fairness preference, Caliskan-Demirag *et al.* [7] revealed that it could promote channel coordination under either linear or nonlinear demand; Niu *et al.* [34] analyzed the influence of channel power and fairness concern on whether to open an online direct channel or not, found that the profit of the retailer may decrease in its channel power, and the fairness concern of the supplier may effectively reduce its incentives to open an online channel; Li *et al.* [35] shown that the fairness concern of the retailer shrunk the stability of supply chain system more than that of the manufacturer, and the stable region decreased in the fairness concern of the retailer.

Regarding reciprocal preference, Du *et al.* [36] found that the reciprocal intention played a very important role in decision making and would thereby significantly change the equilibria of the supply chain, furthermore the reciprocal intention made it possible for a simple wholesale-price contract to coordinate an acrimonious supply chain, which was impossible absolutely in the traditional self-interest supply chain; Su *et al.* [11] investigated the influence of the reciprocal behavior on the incentive mechanism between the remanufacturer and the collector in the construction and demolition waste recycling industry, and found that the reciprocity simulated the remanufacturer to save cost in the incentive mechanism, the collector to implement higher effort in waste-recycling.

Regarding altruistic preference, Ge *et al.* [37] developed an evolutionary model to characterize the effect of altruistic preference in supply network, and found that the profit of the supplier and that of the whole network were enhanced, although they didn't change in a monotonous way; Liu *et al.* [38] shown that altruistic preference enhanced the utilities of logistics service integrator and functional logistics service provider, and the profit of the whole supply chain reached the highest point when logistics service integrator and functional logistics service provider behaved in altruistic way with the same degree; Lin [10] analyzed a supply chain where one manufacturer decided wholesale price, and then two altruistic retailers respectively determined their own retail price and location simultaneously, and revealed that the altruistic preference could improve supply chain performance and made it possible for the derivative version of revenue sharing contract to coordinate supply chain; Zhai *et al.* [39] addressed the impact of altruistic preference on operational efficiency of a capital-constrained supply chain, and shown that altruistic preference would improve financing willingness of the retailer when he had not enough money, while when he had enough capital altruistic preference could sustain high efficiency of supply chain.

The above discussion shows that behavioral preferences have a heavy impact on the decision making and operational performance of the supply chain, and thereby have been attached academic importance in the field of behavioral supply chain. However, little attention have been paid to the influence of behavioral preferences on the joint decision of product greenness and pricing strategy and their interaction on supply chain performance, which will be discussed in this paper.

Moreover, all previous relative literature dealt with behavioral preferences in a separate way under scenario of symmetric information, and thus have never touched asymmetric heterogeneous preferences. For example, the retailer in Lin [10] behaves in an altruistic way and the manufacturer definitely knows the downstream is altruistic instead of other types such as reciprocal, self-interest, and so on, while the retailer in Du *et al.* [36] behaves in a reciprocal way and the manufacturer also surely knows the downstream is reciprocal instead of other types such as altruistic, self-interest, and so on. Such method adopts the traditional assumption, where the behavioral types of supply chain members are homogeneous, fixed, certain, and thereby public symmetric information. Specifically, the manufacturer is assumed to surely know the behavioral type of the retailer, and thereby depend his decision of product greenness and wholesale price on the retailer's behavioral type. But, the behavioral types of supply chain members are actually heterogeneous, various, uncertain, and thereby private asymmetric information. Specifically, the manufacturer does not know whether the retailer is self-interest, altruistic, or of other types, and then can't depend the decision of product greenness and wholesale price on the retailer's behavioral type. The information asymmetry of heterogeneous preferences will change the decision method, process and results of product greenness, product price, and supply chain performance significantly. Therefore, this paper will incorporate the more realistic asymmetric heterogeneous preferences to investigate the optimal decision making of product greenness and pricing strategy; analyze the impact of asymmetric preferences, which means how asymmetric preferences affect the product greenness, price, and supply chain performance; and explore the sensitivity with respect to heterogeneous preferences, which means how heterogeneous preferences change the impact of asymmetric preferences. As shown in previous literature, these important issues have hardly been involved before, and thereby could complement green supply chain literature because of achieving the product greenness and pricing strategy in scenario of asymmetric heterogeneous preferences, and simultaneously complement behavioral supply chain literature because of abandoning the widely adopted unreasonable assumption.

III. PROBLEM DESCRIPTION AND ASSUMPTIONS

A. FRAMEWORK

The green supply chain comprises a manufacturer denoted as him, a retailer denoted as her, and many consumers with environmental awareness, who are willing to pay more for products of higher greenness. The manufacturer behaves in a self-interest way, decides the product greenness and whole price to maximize his profit. The retailer is of multiple types, including self-interest, altruism, and so on. The self-interest retailer decides the retail price to maximize her profit, while the altruistic retailer decides the retail price to maximize her utility increasing in both her own profit and that of the manufacturer. The manufacturer will estimate the response of various retailers, which is theoretically called the reaction function of the retail price.

Under the scenario of symmetric preferences, which is the common hypothesis of previous literature, the manufacturer knows the behavioral type of the retailer exactly and thereby predicts the reaction accurately. If the retailer is self-interest, which has been widely applied in the literature of traditional supply chain, the manufacturer knows that he is facing a self-interest supply chain partner, and thereby decides the product greenness and wholesale price by estimating the retail price decided by the self-interest retailer, defined as the self-interest retail price. If the retailer is altruistic, which has been adopted broadly in the literature of behavioral supply chain, the manufacturer knows that he is facing an altruistic rather than other types such as self-interest supply chain partner, and thereby makes decisions of product greenness and wholesale price by estimating the retail price decided by the altruistic retailer, defined as the altruistic retail price. In this way, the manufacturer decides the product greenness and wholesale price depending on the retailer's behavioral type.

However, under the scenario of asymmetric heterogeneous preferences, the retailer is of multiple types, which result in heterogeneous preferences, and hereby the manufacturer actually does not know the exact type of the retailer because of asymmetric preferences. In such a situation, the retailer still decides her retail price relying on her own behavioral type. The self-interest retailer maximizes profit, while the altruistic retailer maximizes utility. But, the manufacturer can't yet depend his decisions on the type of the retailer anymore because he doesn't know at all. In the approach of Harsanyi doctrine in game theory of incomplete information, the probability distribution of behavioral types is common knowledge. The manufacturer has to estimate the response of various types and hereby speculate his expected profit based on public common knowledge of probability distribution. Then, with the goal of pursuing maximum expected profit, the manufacturer can only make a uniform decision of product greenness and wholesale price independent on the behavioral type of the retailer. In this way, the manufacturer always offers the same product greenness and wholesale price, although the retailer is in fact of different behavioral types.

The following will probe the decision making of product greenness, wholesale price, and retail price under asymmetric heterogeneous preferences, analyze the impact of asymmetric preferences by comparing the results with those of symmetric preferences, and explore how the impact is sensitive with respect to heterogeneous preferences.

B. ASSUMPTIONS

1) PRODUCT GREENNESS

The product greenness is defined as the degree of non-green ingredients emission reduction, where non-green ingredients include lead and its compounds, mercury and its compounds, cadmium and its compounds, hexavalent chromium, polybrominated biphenyls, asbestos, and so on. The manufacturer will enhance the product greenness to achieve sustainable competitiveness by investing in green technology, which can reduce the emission of non-green ingredients. The green investment is a kind of one-shot input, and usually burdens considerable cost. In the mathematical model, the green investment cost increases in the marginal coefficient and the quadratic product greenness monotonously. Furthermore, the marginal cost coefficient of green investment is assumed to be sufficiently large compared with all other parameters and decision variables, which has been widely adopted in previous literature, such as Liu *et al.* [40], Swami and Shah [41], Ji *et al.* [42], and so on.

2) HETEROGENEOUS PREFERENCES

The self-interest manufacturer decides the product greenness and wholesale price to maximize his profit. However, the retailer is of multiple types. To simplify the mathematical process, the following only discusses two types, self-interest and altruistic preference, which does not lose generality and universality because the method can be extended to various preferences such as fairness, reciprocity, jealousy, and so on. The self-interest retailer decides the retail price to maximize her profit, while the altruistic retailer maximizes her utility increasing in both her own profit and that of the manufacturer, which is illustrated in [10], [38] and the following Equation (3). Under the extremely weak altruism, the altruistic strength approaches the limit 0, where the utility in the case of altruistic preference actually equals the profit in the case of self-interest preference. Consequently, the altruistic strength also shows the degree of the difference between self-interest and altruistic preferences. In this sense, the heterogeneity of preferences can been quantized as the altruistic strength.

3) ASYMMETRIC PREFERENCES

The behavioral types of the retailer are various, either self-interest or altruistic, and thereby asymmetric information, by which the manufacturer does not know the exact type of the retailer. In the approach of Harsanyi doctrine in game theory of incomplete information, the probability distribution of each type is common knowledge, by which the manufacturer is supposed to know the probability of self-interest type and that of altruistic type. When the self-interest probability approaches limit 1, the manufacturer knows that the retailer is self-interest surely, while at the other limit of altruistic probability 1 the manufacturer knows that the retailer is altruistic definitely. In this sense, the asymmetric degree of preferences can been quantized as the probability of each type. However, the symmetric preferences in previous literature contain only the extreme points 0 and 1 actually. So, asymmetric preferences covering the whole range from 0 to 1 have never been touched before.

4) MARKET DEMAND

The market is sensitive to the product greenness and retail price simultaneously. The higher greenness, the lower price, the more demand. The greenness sensitive coefficient is represented as consumer environmental awareness (CEA). The market demand monotonously increases in the product greenness and consumer environmental awareness, while monotonously decreases in the retail price and price-sensitive coefficient [30], [43]. In order to focus on analyzing the side of product greenness, the price sensitive coefficient is simplified to 1, which is similar to the approach of Nie and Du [44].

C. NOTATIONS

1) SYMBOLS

The supply chain consists of a manufacturer and a retailer.

m : Manufacturer, he, his.

r : Retailer, she, her.

2) PARAMETERS

The parameters of the supply chain are listed as follows.

a : Maximum potential demand.

b : Price sensitive coefficient of demand, simplified to 1 in the approach of [44].

θ : Greenness sensitive coefficient of demand.

d : Market demand, $d = a - p + \theta e$, similar to [30], [43], where e denotes the product greenness, one of the decision variables of the manufacturer; p denotes the retail price, the decision variable of the retailer.

k : Marginal coefficient of green investment, sufficiently large compared with other parameters and decision variables, similar to [40]–[42].

c : Unit production cost of the manufacturer, $0 < c < a$.

ρ : Altruistic strength, describing how mach attention paid to the profits of others. When compared with the self-interest case, it denotes the heterogeneity of preferences also. Usually, it is subject to the constraint $0 < \rho < 1$ [10], [38]. The upper limit less than 1 means that one's own profit is preferred to others although both can enhance utility, while the lower limit actually returns to the self-interest case.

δ : Probability of self-interest retailer, $0 < \delta < 1$, $\delta' = 1 - \delta$ denoted the altruistic probability, both together representing the probability distribution of heterogeneous preferences. According to the classical approach of modeling asymmetric information set by Spence [45], the objective distribution of possible types is publicly known and common knowledge of all supply chain member, and thereby δ is always taken as a given constant, which can be found in textbooks such as [46] and also is widely adopted in supply chain literature in scenario of asymmetric information such as Ni *et al.* [47].

π_m : Profit of the manufacturer.

π_{m-sf} : Profit of the manufacturer cooperating with a self-interest retailer.

π_{m-ar} : Profit of the manufacturer cooperating with an altruistic retailer.

π_r : Profit of the retailer.

π_{r-sf} : Profit of the self-interest retailer.

π_{r-ar} : Profit of the altruistic retailer.

u_{r-ar} : Utility of the altruistic retailer.

3) DECISION VARIABLES

The manufacturer decides the product greenness and wholesale price, then the retailer decides the retail price, which are described as follows.

e : Product greenness, $0 < e < 1$, the degree of non-green ingredients emission reduction. The non-green ingredients include lead and its compounds, mercury and its compounds, cadmium and its compounds, hexavalent chromium, poly-brominated biphenyls, asbestos, and so on.

e_{sf} : Product greenness to the self-interest retailer.

e_{ar} : Product greenness to the altruistic retailer.

w : Wholesale price.

w_{sf} : Wholesale price to the self-interest retailer.

w_{ar} : Wholesale price to the altruistic retailer.

p : Retail price.

p_{sf} : Retail price decided by the self-interest retailer, self-interest retail price for short.

p_{ar} : Retail price decided by the altruistic retailer, altruistic retail price for short.

4) SUPERSCRIPTS

The optimal decision making and relevant results under asymmetric and symmetric preferences are distinguished by superscripts as follows.

Y^* : Optimal.

$\bar{Y}$: Under asymmetric preferences.

Y : Under symmetric preferences.

$\tilde{\bar{Y}}$: Reaction function.

IV. OPTIMAL DECISION MAKING OF PRODUCT GREENNESS AND PRICE

This section will explore the decision making of product greenness and price to answer the first key question what is the optimal product greenness and pricing strategy of the supply chain under asymmetric heterogeneous preferences. Sequentially, the manufacture makes a decision of product greenness and wholesale price, and then the retailer decides retail price. The approach of reasoning backward is adopted to attain the equilibria.

A. REACTION FUNCTION OF RETAIL PRICE

On the one hand, the self-interest retailer decides her retail price to maximize her own profit, represented by

$$\bar{\pi}_{r-sf} = (\bar{p}_{sf} - \bar{w})(a - \bar{p}_{sf} + \theta\bar{e}) \tag{1}$$

The first and second derivative of $\bar{\pi}_{r-sf}$ with respect to $\bar{p}_{sf}$ are $\partial\bar{\pi}_{r-sf}/\partial\bar{p}_{sf} = a - 2\bar{p}_{sf} + \bar{w} + \theta\bar{e}$ and $\partial^2\bar{\pi}_{r-sf}/\partial\bar{p}_{sf}^2 = -2$ respectively. Because of $\partial^2\bar{\pi}_{r-sf}/\partial\bar{p}_{sf}^2 < 0$, there is only one optimal solution, that is, a unique reaction function of the retail price. Then, according to the first order condition (FOD) $\partial\bar{\pi}_{r-sf}/\partial\bar{p}_{sf} = 0$, the retail price response function of the self-interest retailer is

$$\tilde{\bar{p}}_{sf} = \frac{1}{2}(a + \bar{w} + \theta\bar{e}) \tag{2}$$

On the other hand, the altruistic retailer decides her retail price to maximize utility up to her own profit and that of the manufacturer, represented by

$$\bar{u}_{r-ar} = \bar{\pi}_{r-ar} + \rho E(\bar{\pi}_m) \tag{3}$$

where $\bar{\pi}_{r-ar} = (\bar{p}_{ar} - \bar{w})(a - \bar{p}_{ar} + \theta\bar{e})$ denotes the profit of the altruistic retailer, ρ indicates the altruistic strength, $E(\bar{\pi}_m) = \delta(\bar{w} - c)(a - \tilde{\bar{p}}_{sf} + \theta\bar{e}) + (1 - \delta)(\bar{w} - c)(a - \tilde{\bar{p}}_{ar} + \theta\bar{e}) - k\bar{e}^2/2$ describes the expected profit of the manufacturer. Because altruistic strength is always positive, the utility of the altruistic retailer increases in both her own profit $\bar{\pi}_{r-ar}$ and that of the manufacturer $E(\bar{\pi}_m)$. Then, substituting $\bar{\pi}_{r-ar}$ and $E(\bar{\pi}_m)$ into $\bar{u}_{r-ar}$, yields

$$\bar{u}_{r-ar} = (\bar{p}_{ar} - \bar{w})(a - \bar{p}_{ar} + \theta\bar{e}) + \rho[\delta(\bar{w} - c)(a - \bar{p}_{sf} + \theta\bar{e}) + (1 - \delta)(\bar{w} - c)(a - \bar{p}_{ar} + \theta\bar{e})] - \frac{1}{2}\rho k\bar{e}^2 \tag{4}$$

The first and second derivative of $\bar{u}_{r-ar}$ with respect to $\bar{p}_{sf}$ is$\partial\bar{u}_{r-ar}/\partial\bar{p}_{ar} = a - 2\bar{p}_{ar} + \theta\bar{e} + \bar{w} - \rho(1 - \delta)(\bar{w} - c)$ and $\partial\bar{u}_{r-ar}^2/\partial\bar{p}_{ar}^2 = -2$ respectively. From $\partial\bar{u}_{r-ar}^2/\partial\bar{p}_{ar}^2 < 0$, there is only one unique optimal solution, that is, a unique reaction function of retail price. According to the first order condition $\partial\bar{u}_{r-ar}/\partial\bar{p}_{ar} = 0$, the retail price response function of the altruistic retailer is

$$\tilde{\bar{p}}_{ar} = \frac{1}{2}[a + \bar{w} + \theta\bar{e} - \rho(1 - \delta)(\bar{w} - c)] \tag{5}$$

B. OPTIMAL PRODUCT GREENNESS AND WHOLESALE PRICE DECIDED BY THE MANUFACTURE

The manufacturer wants to maximize his expected profit shown as the above $E(\bar{\pi}_m)$. Substituting the above response function (2) and (5) into $E(\bar{\pi}_m)$, with the decision variables, the product greenness and the wholesale price, yields

$$E(\bar{\pi}_m)=\frac{1}{2}(\bar{w}-c)[a-\bar{w}+\theta\bar{e}+\rho(1-\delta)^2(\bar{w}-c)]-\frac{1}{2}k\bar{e}^2 \tag{6}$$

The Hessian matrix of $E(\bar{\pi}_m)$ on the decision variables $\bar{w}$ and $\bar{e}$ of the manufacturer is $H = \begin{bmatrix} \rho\delta^2-2\delta\rho+\rho-1 & \frac{\theta}{2} \\ \frac{\theta}{2} & -k \end{bmatrix}$. It is clear that $k > \frac{\theta^2}{4[1-\rho(1-\delta)^2]}$ because k is sufficiently large. Then, H is surely a negative matrix, and hereby there is a unique optimal solution. Thus, according to the first order condition $\frac{\partial E(\bar{\pi}_m)}{\partial \bar{w}} = 0$ and $\frac{\partial E(\bar{\pi}_m)}{\partial \bar{e}} = 0$, the optimal product greenness and wholesale price decided by the manufacturer are receptively

$$\bar{e}^* = \frac{\theta(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2} \tag{7}$$

$$\bar{w}^* = c + \frac{2k(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2} \tag{8}$$

C. OPTIMAL RETAIL PRICE DECIDED BY THE RETAILER

The self-interest retailer knows the above product greenness and wholesale price decided by the manufacturer revealed in (7) and (8), and decides her retail price in the light of her own reaction function illustrated in (2) to maximize her profit. Substituting (7) and (8) into (2), the optimal retail price decide by the self-interest retailer is

$$\bar{p}^*_{sf} = c + \frac{k(a-c)[1+2(1-\rho)+2\rho\delta(2-\delta)]}{4k[1-\rho(1-\delta)^2]-\theta^2} \tag{9}$$

The altruistic retailer also knows the above product greenness and wholesale price decided by the manufacturer revealed in (7) and (8), and decides her retail price in the light of her own reaction function illustrated in (5) to maximize her utility instead of profit. Substituting (7) and (8) into (5), the optimal retail price decided by the altruistic retailer is

$$\bar{p}^*_{ar} = c + \frac{k(a-c)[3(1-\rho)+\rho\delta(5-2\delta)]}{4k[1-\rho(1-\delta)^2]-\theta^2} \tag{10}$$

Comparing (9) and (10), it is clear that the retail price changes with the behavioral type of the retailer, namely, the retailer will decide her retail price according to her own behavioral type. Furthermore, the self-interest retail price is always higher than the altruistic retail price, and their difference increase in the altruistic strength. The self-interest retailer cares about her own profit only, while the altruistic retailer cares not only her own profit but also that of the manufacturer. The altruistic retailer behaves to maximize her utility instead of profit, but the self-interest retailer pursues maximum profit instead of utility. Regarding the altruistic retailer, although a lower retail price reduces her marginal profit directly, it enhances the marginal profit of the manufacturer and sales volume indirectly, which ultimately raises her utility.

D. OPTIMAL SUPPLY CHAIN PERFORMANCE

Supply chain performance is represented by the profits of the manufacturer and the self-interest retailer, and the altruistic retailer's utility and profit. It is up to the product greenness and price, and hereby reflects the outcomes of the above optimal decision making logically.

From (6), (7) and (8), the optimal expected profit of the manufacturer is

$$E(\bar{\pi}^*_m) = \frac{k(a-c)^2}{2\{4k[1-\rho(1-\delta)^2]-\theta^2\}} \tag{11}$$

From (1), (7), (8) and (9), the optimal profit of the self-interest retailer is

$$\bar{\pi}^*_{r-sf} = \frac{k^2(a-c)^2[1-2\rho(1-\delta)^2]^2}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2} \tag{12}$$

Summing up (11) and (12), it is very interesting that both the profit of the manufacturer and that of the self-interest retailer are relevant to the altruistic preference although they behave in a purely self-interest way. Their profits are affected by the behavioral types of others except their own.

From (4), (7), (8), and (10), the optimal utility and profit of the altruistic retailer are respectively

$$\bar{u}^*_{r-ar} = k(a-c)^2 \times \frac{2k(1-2\delta)^2(1-\delta)^2\rho^2+[4k-8k(1-\delta)^2-\theta^2]\rho+2k}{2\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2} \tag{13}$$

and

$$\bar{\pi}^*_{r-ar} = \frac{k^2(a-c)^2[1+(1-\delta)(2\delta-3)\rho][1+(1-\delta)(2\delta-1)\rho]}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2} \tag{14}$$

Comparing (12) and (14), it can be revealed that the profit of the self-interest retailer always is bigger than that of the altruistic retailer, which is consistent with the above finding that the self-interest retailer always chooses a higher retail price than the altruistic retailer does.

V. IMPACT OF ASYMMETRIC PREFERENCES

This section will investigate the impact of asymmetric preferences to answer the second question how asymmetric preferences affect the product greenness, price, and supply chain performance. The impact of asymmetric preferences, is defined as the difference between scenarios of asymmetric and symmetric preferences. In the scenario of asymmetric preferences, the manufacturer does not know the behavioral type of the retailer, and decides the product greenness and wholesale price in the approach of Harsanyi doctrine. In the scenario of symmetric preferences, the manufacturer does know the behavioral type of the retailer, either self-interest or altruistic, and thereby decides the product greenness and wholesale price according to the behavioral type of the retailer. The traditional supply chain literature has been exploring the product greenness and price under the condition of symmetric self-interest preference, where the retailer always behaves in a rational way of concerning its own profit. The behavioral supply chain literature has been investigating the product greenness and price under the condition of symmetric altruistic preference, where the retailer always behaves in an irrational way of concerning both its own profit and others. The above section 4 has attained the optimal product greenness and price under asymmetric preferences. By comparing asymmetric and symmetric scenarios, the following will systematically explore how the asymmetric preferences affect the product greenness, price, and supply chain performance shown in several propositions, whose proofs are in the appendix.

A. IMPACT OF ASYMMETRIC PREFERENCES ON PRODUCT GREENNESS

The optimal product greenness under asymmetric preferences is attained in the above (7). In the case of symmetric preferences, the manufacture knows the retailer is of self-interest type where self-interest probability equals 1, or of the altruistic type where altruistic probability equals 1. Therefore, by letting $\delta = 1$ in (7), the optimal product greenness to the self-interest retailer under symmetric preferences is

$$e_{sf}^* = \frac{\theta(a-c)}{4k-\theta^2} \tag{15}$$

while by letting $\delta = 0$ in (7), the optimal product greenness to the altruistic retailer under symmetric preferences is

$$e_{ar}^* = \frac{\theta(a-c)}{4k(1-\rho)-\theta^2} \tag{16}$$

Thus, the average product greenness under symmetric preferences is

$$E(e^*) = \delta e_{sf}^* + (1-\delta)e_{ar}^* = \frac{\theta(a-c)[4k(1-\delta\rho)-\theta^2]}{(4k-\theta^2)[4k(1-\rho)-\theta^2]} \tag{17}$$

Then, from the above (7), (15), (16), and (17), the impact of asymmetric preferences on product greenness, illustrated by the difference between those under asymmetric and symmetric preferences, is concluded as

Proposition 1: Asymmetric preferences reduce the average product greenness $\bar{e}^* < E(e^*)$, but change the individual product greenness to every type of retailer depending on behavioral types. The product greenness to the self-interest retailer is enhanced $e_{sf}^* < \bar{e}^*$, while that to the altruistic retailer is reduced $\bar{e}^* < e_{ar}^*$.

It characterizes the influence direction of asymmetric preferences on product greenness. On the whole, asymmetric preferences always reduce the average product greenness, no matter how the heterogeneity and asymmetry of preferences vary. For individuals, the influence direction of asymmetric preferences changes with the behavioral type of the retailer. The product greenness to an uncertain type of retailer under asymmetric preferences is bigger than that to a self-interest retailer under symmetric preferences, whereas is smaller than that to an altruistic retailer under symmetric preferences. Summarily, asymmetric preferences will reduce the product greenness to the altruistic retailer while enhancing that to the self-interest retailer. The former dominates, which results in lower average product greenness.

B. IMPACT OF ASYMMETRIC PREFERENCES ON PRODUCT PRICE

1) IMPACT OF ASYMMETRIC PREFERENCES ON WHOLESALE PRICE

The wholesale price under asymmetric preferences is attained in (8). Under symmetric preferences, the manufacture knows the behavioral type of the retailer, self-interest or altruistic. Then, by letting $\delta = 1$ in (8), the optimal wholesale price to the self-interest retailer under symmetric preferences is

$$w_{sf}^* = c + \frac{2k(a-c)}{4k-\theta^2} \tag{18}$$

while by letting $\delta = 0$ in (8), the optimal wholesale price to the altruistic retailer under symmetric preferences is

$$w_{ar}^* = c + \frac{2k(a-c)}{4k(1-\rho)-\theta^2} \tag{19}$$

Therefore, the average wholesale price under symmetric preferences can be shown as

$$\begin{aligned} E(w^*) &= \delta w_{sf}^* + (1-\delta)w_{ar}^* \\ &= c + \frac{2k(a-c)[4k(1-\delta\rho)-\theta^2]}{(4k-\theta^2)[4k(1-\rho)-\theta^2]} \end{aligned} \tag{20}$$

Then, from the above (8), (18), (19), and (20), the impact of asymmetric preferences on the wholesale price, illustrated by the difference between those under asymmetric and symmetric preferences, is concluded as

Proposition 2: Asymmetric preferences reduce the average wholesale price $\bar{w}^* < E(w^*)$, but change the individual wholesale price to every type of retailer depending on behavioral types. The wholesale price to the self-interest retailer is enhanced $w_{sf}^* < \bar{w}^*$, while that to the altruistic retailer is reduced $\bar{w}^* < w_{ar}^*$.

It characterizes the influence direction of asymmetric preferences on wholesale prices. On the whole, asymmetric preferences always reduce the average wholesale price, no matter how the heterogeneity and asymmetry of preferences vary. For individuals, the influence direction of asymmetric preferences is up to the behavioral type of the retailer. The wholesale price to an uncertain type of retailer under asymmetric preferences is bigger than that to a self-interest retailer under symmetric preferences, whereas is smaller than that to an altruistic retailer under symmetric preferences. Asymmetric preferences will reduce the wholesale price to the altruistic retailer, while enhancing that to the self-interest retailer. The former dominates, which results in a lower average wholesale price. Integrating proposition 1 and 2, it is clear that the influence direction of asymmetric preferences on wholesale price is similar to that on product greenness.

Moreover, although asymmetric preferences will reduce the wholesale price averagely, the altruistic preference will raise the wholesale price because $w^*_{sf} < w^*_{ar}$ definitely. Thus, the influence from the type of behavioral preferences is different from that from the asymmetric information of behavioral preferences. However, previous literature always focuses on the type of behavioral preferences, analyzes its influence by comparing results under different behavioral types. But, this paper turns to the asymmetric information of behavioral preferences, probes its influence by comparing those under asymmetric and symmetric preferences, which is never touched before.

2) IMPACT OF ASYMMETRIC PREFERENCES ON RETAIL PRICE

The retail price under asymmetric preferences decided by the self-interest retailer is attained in the above (9), where the behavioral type of the retailer is self-interest surely. Then, by letting $\delta = 1$ in (9), the optimal self-interest retail price under symmetric preferences is

$$p^*_{sf} = c + \frac{3k(a-c)}{4k-\theta^2} \tag{21}$$

The retail price under asymmetric preferences decided by the altruistic retailer is defined in (10), where the behavioral type of the retailer is altruistic surely. Then, by letting $\delta = 0$ in (10), the optimal altruistic retail price under symmetric preferences is

$$p^*_{ar} = c + \frac{3k(a-c)(1-\rho)}{4k(1-\rho)-\theta^2} \tag{22}$$

From the above (9) and (21), (10) and (22), the impact of asymmetric preferences on the retail price, illustrated by the difference between those under asymmetric and symmetric preferences, is concluded as

Proposition 3: Asymmetric preferences change the retail price depending on the retailer's behavioral type. The self-interest retail price is enhanced $\bar{p}^*_{sf} > p^*_{sf}$, while the altruistic retail price is reduced $\bar{p}^*_{ar} < p^*_{ar}$.

It characterizes the influence direction of asymmetric preferences on the retail price. Apparently, it is up to the behavioral type of the retailer. The self-interest retailer will raise her retail price under asymmetric preferences, while the altruistic retailer will reduce. It is similar to the case of the wholesale price, which also depends on the behavioral type of the retailer. It actually results from the gradual transitive relationship in the supply chain. For the self-interest retailer, the upstream manufacturer raises the wholesale price, which enhances her cost and thereby requires a higher retail price. For the altruistic retailer, the upstream manufacturer reduces the wholesale price, which cuts down her cost and thereby requires a lower retail price.

In this perspective, altruistic preference is advantageous to the development of a green supply chain because it will decrease product prices including wholesale and retail prices. However, such a positive effect will been restricted by the asymmetric information of behavioral preferences. Under asymmetric preferences, the self-interest preference will increase product price while the altruistic preference will decrease. It is unreasonable to ignore the essential attribute of asymmetric information when incorporating the behavioral preferences into the supply chain, which however is common in previous literature. Thus, this paper will investigate heterogeneous preferences with asymmetric information.

C. IMPACT OF ASYMMETRIC PREFERENCES ON SUPPLY CHAIN PERFORMANCE

Supply chain performance is shown as the profits of the manufacturer and the self-interest retailer, and the altruistic retailer's utility and profit. The impact of asymmetric preferences on supply chain performance is represented by the difference between those under asymmetric and symmetric preferences.

Regarding the manufacturer, the expected profit under asymmetric preferences is attained in (11). In case of $\delta = 1$, the manufacturer knows that the downstream is a self-interest retailer definitely. By letting $\delta = 1$ in (11), the optimal profit of the manufacturer cooperating with a self-interest retailer under symmetric preferences is

$$\pi^*_{m-sf} = \frac{k(a-c)^2}{2(4k-\theta^2)} \tag{23}$$

In case of $\delta = 0$, the manufacturer knows that the downstream is an altruistic retailer definitely. By letting $\delta = 0$ in (11), the optimal profit of manufacturer cooperating with an altruistic retailer under symmetric preferences is

$$\pi^*_{m-ar} = \frac{k(a-c)^2}{2[4k(1-\rho)-\theta^2]} \tag{24}$$

Then, combining the above two sides, in approach of expectation rule, the average profit of the manufacturer under symmetric preferences is

$$\begin{aligned} E(\pi^*_m) &= \delta\pi^*_{m-sf} + (1-\delta)\pi^*_{m-ar} \\ &= \frac{k(a-c)^2[4k(1-\delta\rho)-\theta^2]}{2(4k-\theta^2)[4k(1-\rho)-\theta^2]} \end{aligned} \tag{25}$$

Regarding the self-interest retailer, the profit under asymmetric preferences is attained in the above (12), where $\delta = 1$ indicates that the manufacturer knows he is cooperating with a self-interest retailer. By letting $\delta = 1$ in the above (12), the optimal profit of the self-interest retailer under symmetric preferences is

$$\pi^*_{r-sf} = \frac{k^2(a-c)^2}{(4k-\theta^2)^2}. \tag{26}$$

Regarding the altruistic retailer, the profit under asymmetric preferences is attained in (14), where $\delta = 0$ indicates that the manufacturer knows he is cooperating with an altruistic retailer. By letting $\delta = 0$ in (14), the profit of the altruistic retailer under asymmetric preferences is

$$\pi^*_{r-ar} = \frac{k^2(a-c)^2(1-3\rho)(1-\rho)}{[4k(1-\rho)-\theta^2]^2} \tag{27}$$

Moreover, the utility under asymmetric preferences is attained in the above (13), where $\delta = 0$ indicates that the manufacturer knows he is cooperating with an altruistic retailer. Then, letting $\delta = 0$ in (13), the optimal utility of the altruistic retailer under symmetric preferences is

$$u^*_{r-ar} = \frac{k(a-c)^2(2k\rho^2-4k\rho+2k-\theta^2\rho)}{2[4k(1-\rho)-\theta^2]^2} \tag{28}$$

By comparing results under asymmetric and symmetric preferences one by one, the impact of asymmetric preferences on supply chain performance, illustrated by the difference between those under asymmetric and symmetric preferences, is concluded as

Proposition 4: Asymmetric preferences decrease surely the manufacturer's profit, $E(\bar{\pi}^*_m) < E(\pi^*_m)$; and reduce the self-interest retailer's profit with exceptional A representing the domain of $\frac{2}{3(1-\delta)^2} \le \rho < 1$ and $0 < \delta < 1-\sqrt{\frac{2}{3}}$, that is, $\bar{\pi}^*_{r-sf} < \pi^*_{r-sf}$ unless domain A; but enhance the altruistic retailer's profit without any exception $\bar{\pi}^*_{r-ar} > \pi^*_{r-ar}$, while enhance the altruistic retailer's utility with exception of the same domain A, namely $\bar{u}^*_{r-ar} > u^*_{r-ar}$ unless domain A.

It characterizes the influence direction of asymmetric preferences on supply chain performance, which includes the following four aspects.

First, the profit of the manufacture will be reduced by asymmetric preferences definitely, no matter how the heterogeneity and asymmetry of preferences vary. It can be found that $\pi^*_{m-ar} > \pi^*_{m-sf}$, which means that the manufacture can gain more profits when cooperating with an altruistic retailer than with a self-interest retailer. More profits are useful for the manufacturer to implement green investment. In this sense, the altruistic preference is advantageous to the development of a green supply chain, while the asymmetric information of behavioral preferences isn't. However, previous literature hardly touched and distinguished them.

Second, the profit of the self-interest retailer will be reduced by asymmetric preferences with some exception illustrated as domain A in figure 1.

In figure 1, the abscissa parameter of altruistic strength represents the heterogeneity of preferences, and the ordinate parameter of self-interest and altruistic probability denotes the asymmetry of preferences. The way how asymmetric preferences impact the self-interest retailer's profit varies in different domain. On one hand, in the most domain B, which is defined and discussed in detail in the appendix, asymmetric preferences will reduce the profit of the self-interest retailer. On the other hand, in the few domain A, in which the heterogeneity is very strong and the asymmetry is very weak, asymmetric preferences will enhance the profit of

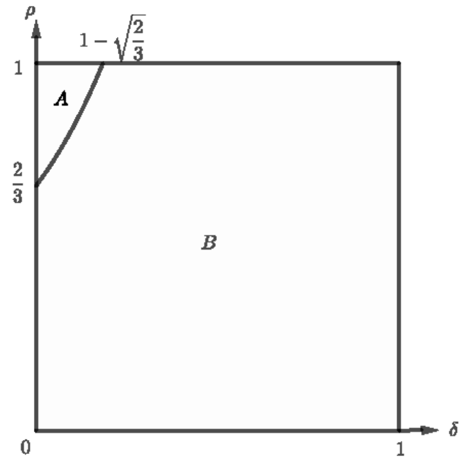

FIGURE 1. Influence direction domain of asymmetric preferences in cases of both the self-interest retailer's profit and the altruistic retailer's utility, where A denotes the exceptional domain.

the self-interest retailer. Therefore, comparing the above two cases, the influence direction of asymmetric preferences on the profit of the self-interest retailer will be changed significantly by the interaction between strong heterogeneity and weak asymmetry, which is called cross effect.

Third, the profit of the altruistic retailer will definitely be enhanced by asymmetric preferences, no matter how the heterogeneity and the asymmetry of preferences vary. Comparing with the case of the self-interest retailer's profit, how asymmetric preferences influence the profit of the retailer depends on the behavioral type. Although the profit of the self-interest retailer is reduced, that of the altruistic retailer is enhanced, which can be treated as a kind of return from the altruistic behavior concerning others.

Finally, the utility of the altruistic retailer will be enhanced with some exception, also illustrated as domain A of figure 1. It is very interesting that the exceptional domain is the same as that in case of the self-interest retailer's profit, but their directions are always contrary. Specifically, in the most domain B, asymmetric preferences will increase the utility of the altruistic retailer but decrease the profit of the self-interest retailer. In the few domain A, asymmetric preferences will decrease the utility of the altruistic retailer but increase the profit of the self-interest retailer. Similarly, the cross effect between strong heterogeneity and weak asymmetry also changes the influence direction of asymmetric preferences on the utility of the altruistic retailer.

VI. SENSITIVITY WITH RESPECT TO HETEROGENEOUS PREFERENCES

This section will reveal the sensitivity with respect to heterogeneous preferences to answer the third question how heterogeneous preferences change the impact of asymmetric preferences on product greenness, price, and supply chain performance. The optimal decision making of the product greenness and price was attained in section 4, and section 5 obtained the impact of asymmetric preferences on product greenness, price and supply chain performance. On those basis, the following will explore how the above impact of asymmetric preferences will change with heterogeneous preferences. It is different from the sensitivity with respect to symmetric preferences in previous literature, which actually answers how the product greenness, price, and supply chain performance changes with the strength of l preferences under symmetric information. However, the sensitivity with respect to heterogeneous preferences answers how the impact of asymmetric preferences on product greenness, price and supply chain performance, changes with the heterogeneity of preferences. In particular, the subject is the impact of asymmetric preferences on product greenness, price, and supply chain performance, instead of the product greenness, price, and supply chain performance in previous literature; the driver is the heterogeneous preferences instead of symmetric preferences in previous literature.

A. SENSITIVITY OF PRODUCT GREENNESS WITH RESPECTIVE TO HETEROGENEOUS PREFERENCES

The sensitivity of the optimal product greenness with respect to heterogeneous preferences, which means how the impact of asymmetric preferences on product greenness changes with the heterogeneity of preferences, is concluded as

Proposition 5: The impact of asymmetric preferences on product greenness increases in heterogeneous preferences. The bigger heterogeneity of preferences, the more the average product greenness is reduced by asymmetric preferences $0 < \frac{\partial[E(e^*)-\bar{e}^*]}{\partial\rho}$*, the more the product greenness to the self-interest retailer is enhanced by asymmetric preferences* $0 < \frac{\partial(\bar{e}^*-e^*_{sf})}{\partial\rho}$*, and the more the product greenness to the altruistic retailer is reduced by asymmetric preferences* $0 < \frac{\partial(e^*_{ar}-\bar{e}^*)}{\partial\rho}$*.*

On the whole, the impact of asymmetric preferences on average product greenness increases in heterogeneous preferences monotonically. By integrating with proposition 1, it is clear that asymmetric preferences will reduce the average product greenness, and the degree of reduction increases in the heterogeneity of preferences. For individuals, both the impact of asymmetric preferences on the product greenness to the self-interest, and the impact on that to the altruistic retailer increase in heterogeneous preferences monotonically, although according to proposition 1 they change in opposite directions. Specifically, asymmetric preferences will raise the product greenness to the self-interest retailer while reducing that to the altruistic retailer.

Therefore, asymmetric heterogeneous preferences actually are advantageous to the development of a green supply chain, although they will result in the uncertainty and asymmetric information of behavioral types. Asymmetric preferences will enhance the average product greenness, heterogeneous preferences will promote the increasing degree, which has never been touched before.

B. SENSITIVITY OF PRODUCT PRICE WITH RESPECT TO HETEROGENEOUS PREFERENCES

1) SENSITIVITY OF WHOLESALE PRICE WITH RESPECT TO HETEROGENEOUS PREFERENCES

The sensitivity of the optimal wholesale price with respect to heterogeneous preferences, which describes how the impact of asymmetric preferences on wholesale price changes with heterogeneous preferences, is concluded as

Proposition 6: The impact of asymmetric preferences on wholesale price increases in heterogeneous preferences. The bigger heterogeneity of preferences, the more the average wholesale price is reduced by asymmetric preferences $0 < \frac{\partial[E(w^*)-\bar{w}^*]}{\partial\rho}$*, the more the wholesale price to the self-interest retailer is enhanced by asymmetric preferences* $0 < \frac{\partial(\bar{w}^*-w^*_{sf})}{\partial\rho}$*, and the more the wholesale price to the altruistic retailer is reduced by asymmetric preferences* $0 < \frac{\partial(w^*_{ar}-\bar{w}^*)}{\partial\rho}$*.*

On the whole, the impact of asymmetric preferences on the average wholesale price increases in the heterogeneity of preferences monotonically. By integrating with proposition 2, asymmetric preferences will reduce the average wholesale price to a greater extent in case of stronger heterogeneity of preferences surely. For individuals, the impact of asymmetric preferences on the wholesale price to both the self-interest and altruistic retailer increases in heterogeneous preferences monotonically also. Asymmetric preferences will change the wholesale price to a greater extent as the heterogeneity of preferences expands, although the wholesale price to the self-interest retailer is enhanced while that to the altruistic retailer is reduced by asymmetric preferences according to the above proposition 2.

Consequently, the wholesale price is actually determined by various drivers, which should be probed carefully and separately. Comparatively, the altruistic preference can slow down the decreasing trend of wholesale price resulting from asymmetric preferences, which can make the manufacturer to accumulate green investments, and thereby is useful to the development of a green supply chain.

2) SENSITIVITY OF RETAIL PRICE WITH RESPECT TO HETEROGENEOUS PREFERENCES

The sensitivity of the optimal retail price with respect to heterogeneous preferences, which means how the impact of asymmetric preferences on the retail price changes with heterogeneous preferences, is concluded as

Proposition 7: The impact of asymmetric preferences on the retail price increases in heterogeneous preferences. The bigger heterogeneity of preferences, the more the self-interest retail price is enhanced by asymmetric preferences $0 < \frac{\partial(\bar{p}^*_{sf}-p^*_{sf})}{\partial\rho}$*, the more the altruistic retail price is reduced by asymmetric preferences* $0 < \frac{\partial(p^*_{ar}-\bar{p}^*_{ar})}{\partial\rho}$*.*

The impact of asymmetric preferences on the retail price also monotonically increases in heterogeneous preferences. Therefore, by integrating with proposition 3, asymmetric preferences will reduce the altruistic retail price whereas enhance the self-interest retail price to a greater extent as the heterogeneity of preferences becomes strong.

Summing up the above proposition 1, 2, 3, 5, 6, and 7, yields the following corollary.

Corollary 1: The direction and extent of the influence are up to different factors, namely, determined by asymmetric preferences and heterogeneous preferences respectively.

On one hand, the influence direction, which answers whether it is increased or decreased, is determined by asymmetric preferences. For example, the above proposition 1 reveals that asymmetric preferences will decrease the average product greenness and the product greenness to the altruistic retailer, while increase that to the self-interest retailer. On the other hand, the influence extent, which answers how much it is affected, is determined by heterogeneous preferences. For example, the above proposition 5 reveals that the average product greenness, the product greenness to the self-interest retailer, and the product greenness to the altruistic retailer, all will change to a greater extent as the heterogeneity of preferences expands, although the first two points decreases while the final one point increases. It is possible that it is affected in the same direction to a different extent, or in a different direction to the same extent. This finding never occurred in previous literature.

Moreover, distinguishing different influences can separate different factors effectively. Taking proposition 3 and 7 as an example, the impact of altruistic preference, heterogeneity of preferences, and asymmetry of preferences, can be separated one by one in detail. Specially, the altruistic preference itself will increase the retail price, whose influence extent increases in the heterogeneity of preferences. However, the asymmetry of preferences will decrease the retail price, whose influence extent also increases in the heterogeneity of preferences. The influence direction is up to the types and asymmetry of preferences, while the influence extent depends on the heterogeneity of preferences. These three drivers all can change the retail price of a green supply chain, where the influence direction, influence extent, and the dominating factor vary with the combination of behavioral types, strengths, and their probability distribution.

C. SENSITIVITY OF SUPPLY CHAIN PERFORMANCE WITH RESPECT TO HETEROGENEOUS PREFERENCES

Then sensitivity of supply chain performance with respect to heterogeneous preferences, which answers the question how the impact of asymmetric preferences on supply chain performance changes with heterogeneous preferences, where supply chain performance is illustrated by the profits of the manufacturer and the self-interest retailer, and the altruistic retailer's utility and profit, is concluded as

Proposition 8: The impact of asymmetric preferences on supply chain performance increases in heterogeneous preferences. The bigger heterogeneity of preferences, the more the manufacturer's profit is reduced by asymmetric preferences $0 < \frac{\partial[E(\pi_m^*)-E(\bar{\pi}_m^*)]}{\partial\rho}$*; the more the self-interest retailer's profit is decreased by asymmetric preferences with exception of domain C defined by* $\frac{1}{2(1-\delta)^2} < \rho < 1$ *and* $0 < \delta < 1-\sqrt{\frac{1}{2}}$*, namely* $0 < \frac{\partial(\pi_{r-sf}^*-\bar{\pi}_{r-sf}^*)}{\partial\rho}$ *unless domain C; the more the altruistic retailer's profit is enhanced by asymmetric preferences* $0 < \frac{\partial(\bar{\pi}_{r-ar}^*-\pi_{r-ar}^*)}{\partial\rho}$*; the more the altruistic retailer's utility is increased by asymmetric preferences with exception of domain E defined by* $0 < \delta < \frac{1}{2}$ *and* $\frac{1}{4(1-\delta)^2} < \rho < 1$*, namely* $0 < \frac{\partial(\bar{u}_{r-ar}^*-u_{r-ar}^*)}{\partial\rho}$ *unless domain E.*

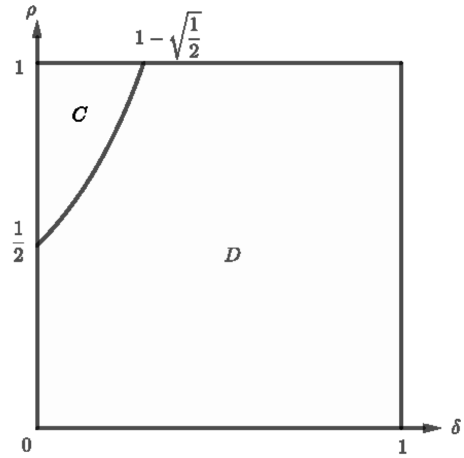

FIGURE 2. Influence extent domain of heterogeneous preferences in case of the self-interest retailer's profit, where C denotes the exceptional domain.

It characterizes the influence extent of asymmetric preferences on supply chain performance, while the influence direction is shown in the above proposition 4.

First, the influence extent of asymmetric preferences on the profit of the manufacture monotonically increases in heterogeneous preferences. The stronger heterogeneity of preferences, the more the profit of the manufacture will be reduced by asymmetric preferences definitely. Furthermore, it can be found that $\pi_{m-ar}^* > \pi_{m-sf}^*$ by which the manufacturer can attain more profits when cooperating with an altruistic retailer than with a self-interest retailer, and additionally $\frac{\partial(\pi_{m-ar}^*-\pi_{m-sf}^*)}{\partial\rho} > 0$ by which the additional profit increases in the altruistic strength. Therefore, the type of preferences, the heterogeneity of preferences and the asymmetry of preferences affect the profit of the manufacture in different way. Specifically, the type of preferences and the asymmetry of preferences determine the influence direction jointly, where the asymmetric information is the dominating factor. The heterogeneity of preferences determines the influence extent, which always monotonically increases in the heterogeneity of preferences regardless of the influence direction. It is consistent with the above corollary 1.

Second, the influence extent of asymmetric preferences on the profit of the self-interest retailer increases in the heterogeneity of preferences with some exception illustrated as domain C in figure 2.

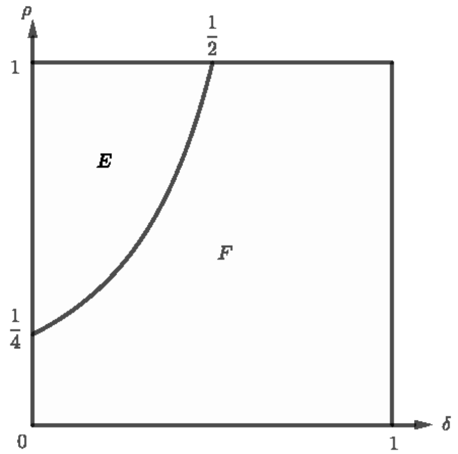

FIGURE 3. Influence extent domain of heterogeneous preferences in case of the altruistic retailer's utility, where E denotes the exceptional domain.

In figure 2, the abscissa parameter of altruistic strength represents the heterogeneity of preferences, and the ordinate parameter of self-interest and altruistic probability denotes the asymmetry of preferences. The extent that asymmetric preferences influence the self-interest retailer's profit varies in different domains. On one hand, in the most domain D, which is defined and discussed in detail in appendix, asymmetric preferences will reduce the self-interest retailer's profit to a greater extent in case of stronger heterogeneity of preferences. On the other hand, in the few domain C denoting exception, asymmetric preferences will enhance the self-interest retailer's profit to a greater extent as the heterogeneity of preferences become stronger. It is clear that in the exceptional domain C, the heterogeneity of preferences is very strong and the asymmetry of preferences is very weak, their intersection changes the influence extent of asymmetric preferences on the self-interest retailer's profit. Compared with figure 1, regarding the self-interest retailer's profit, although the exceptional domain of influence extent is slightly bigger than the exceptional domain of influence direction, cross effect must result from strong heterogeneity and weak asymmetry too.

Third, the influence extent of asymmetric preferences on the altruistic retailer's profit increases in heterogeneous preferences monotonically too. The stronger heterogeneity of preferences, the more the altruistic retailer's profit will be reduced by asymmetric preferences definitely.

Finally, the influence extent of asymmetric preferences on the altruistic retailer's utility increases in the heterogeneity of preferences with some exception illustrated as domain E in figure 3.

The extent that asymmetric preferences influence the self-interest retailer's utility varies in different domains, which is defined by both the abscissa parameter of altruistic strength representing the heterogeneity of preferences and the ordinate parameter of altruistic probability denoting the asymmetry of preferences in figure 3. In the most domain F, which is defined and discussed in appendix in detail, asymmetric preferences will raise the utility of the altruistic retailer to a greater extent as the heterogeneity becomes stronger. However, in the few domain E denoting exception, asymmetric preferences will reduce the utility of the altruistic retailer to a greater extent in case of stronger heterogeneity. Compared with figure 2, although the exceptional domain in case of the altruistic retailer's utility is significantly bigger than the exceptional domain in case of the self-interest retailer's profit, cross effect results from strong heterogeneity and weak asymmetry too.

Summing up the above figure 1, figure 2, and figure 3, which show the exceptional domain of the influence direction and influence extent in cases of the self-interest retailer's profit and the altruistic retailer's utility, denoted as A, C, and E respectively, yields the following corollary about cross effect stemming from strong heterogeneity and weak asymmetry of preferences.

Corollary 2: Regarding the self-interest retailer's profit and the altruistic retailer's utility, the combination of strong heterogeneity and weak asymmetry of preferences leads to cross effect definitely, which changes both the direction of influence from asymmetric preferences and the extent of influence from heterogeneous preferences.

VII. CASE STUDY

A. DATA OF BAIC MOTOR

One of the famous leading state-controlled listed vehicle manufacturers of China, BAIC Motor embedded the green supply chain management into the medium and long-term strategic plan of development in 2016. Moreover, BAIC Motor made a series of concrete measures to implement green supply chain management into practical operation, which ensure all the segments of design, development, production, maintenance, and recovery meet the relevant environmental regulations and standards, and ensure the realization of selecting high-quality suppliers, shortening the product development cycle, improving product quality level, reducing product environmental pollution, and so on. Because of the excellent performance of green supply chain management, BAIC Motor was selected as a typical case by the Ministry of Industry and Information Technology (MIIT) of China in 2018, who issued the National Industrial Green Development Plan of 2016 to 2020.

The market demand of BAIC Motor has been estimated based on the statistical historical data by Wang and Hu [48]. The maximum potential demand is 6 million units per year. The price-sensitive coefficient of demand equals about 200 thousand units per CNY¥10 thousand. The greenness sensitive coefficient of demand, which describes customer environmental awareness, is around 50 thousand units per non-green ingredient emission reduction. The average production cost is CNY¥100 thousand per unit. The marginal cost coefficient of green investment is around CNY¥2 million. All the actual data have been estimated with statistical data and the econometric method by Wang and Hu [48], and are listed in the second column of table 1. Besides, in the theoretic model, the price-sensitive coefficient in the market demand is simplified as standardized 1 to focus

TABLE 1. Data of BAIC motor.

Parameters	Actual data [a]	Standardized data [a]
maximum potential demand	600	30
price sensitive coefficient	20	1
greenness sensitive coefficient	5	0.25
unit production cost	10	0.5
marginal cost coefficient of green investment	200	10

[a] Ten thousand.

on the product greenness, which is widely adopted in supply chain literature such as Nie and Du [44]. In order to be consistent with the theoretic model, the actual data of BAIC Motor should be divided by the standardized parameter of price-sensitive coefficient 20. Then, the standardized data are shown in the third column of table 1.

Additionally, the constraints which ensure economic and operational rationality should be satisfied. For example, the product greenness, represented by the degree of non-green ingredients emission reduction, should be in the interval between 0 and 1, and the wholesale price should be less than the retail price. These require that the heterogeneity of preferences represented by the altruistic strength should be in the range from 0 to 0.32 based on the above real data of BAIC Motor. Of course, the asymmetry of preferences represented by the self-interest and altruistic probability varies freely in the internal 0 to 1.

Comprehensively integrating the above actual data and the theoretic propositions, the impact of asymmetric preferences on product greenness and price, which is illustrated by the difference between those under asymmetric and symmetric preferences, and the sensitivity with respect to heterogeneous preferences, which shows how the impact of asymmetric preferences on product greenness and price changes with heterogeneous preferences, can be calculated numerically.

B. CHANGE OF PRODUCT GREENNESS WITH ASYMMETRIC HETEROGENEOUS PREFERENCES

Based on the above analysis, the product greenness under asymmetric preferences in (7) and that under symmetric preferences in (17) can be achieved respectively with actual data. Then, the sensitivity of product greenness with respect to heterogeneous preferences is illustrated in figure 4, where the altruistic probability is remarked by 0.2 ($\delta = 0.8$), 0.5 ($\delta = 0.5$) and 0.8 ($\delta = 0.2$) directly and separately, the abscissa axis denotes the heterogeneity of preferences, the ordinate axis denotes the product greenness, and results under symmetric and asymmetric information are denoted as dotted line and solid line respectively.

In accordance with proposition 1, the product greenness under asymmetric preferences is always lower than that under symmetric preferences, which is irrelevant with the altruistic probability. Furthermore, the difference between those under asymmetric and symmetric preferences increases in the heterogeneity of preferences, which illustrates and verifies the above proposition 5.

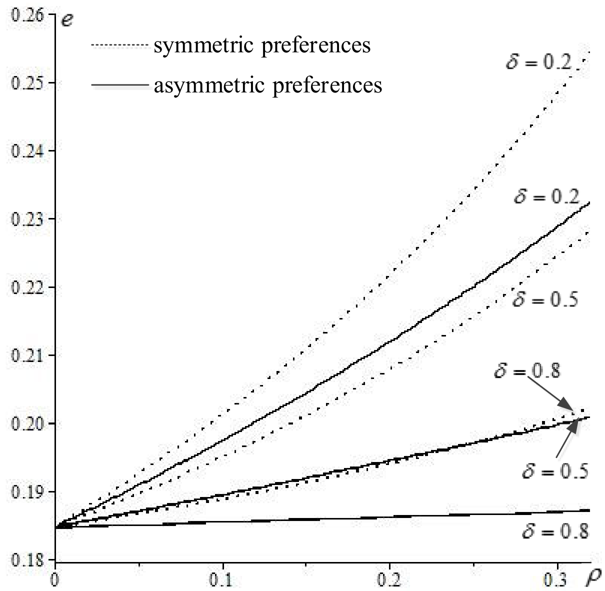

FIGURE 4. Change of product greenness with asymmetric heterogeneous preferences.

Moreover, it can be found that the product greenness under asymmetric preferences always monotonically increases in the heterogeneity of preferences in a nearly linear way, while that under symmetric preferences monotonically increases in a nearly exponential way. Although both the increasing rates raise with the altruistic probability, the former is always bigger than the latter. Especially, in the case of altruistic probability equaling 0.2 ($\delta = 0.8$), the product greenness under asymmetric preferences hardly increases in the heterogeneity of preferences, while that under symmetric preferences increases in a slow and nearly linear way. Additionally, as a pure coincidence, the product greenness in the case of altruistic probability 0.5 ($\delta = 0.5$) under asymmetric preferences is almost the same as that in the case of altruistic probability 0.2 ($\delta = 0.8$) under symmetric preferences. By comparing each case one by one, it can be found that the difference between the product greenness under symmetric and asymmetric preferences increases in both the heterogeneity of preferences represented by the altruistic strength and the asymmetry of preferences represented by the altruistic probability. Consequently, an observation deepening the proposition 1 and 5 can be concluded as follows.

Observation 1: The influence extent of asymmetric preferences on product greenness increases and accelerates in both the heterogeneity and asymmetry of preferences.

C. CHANGE OF PRODUCT PRICE WITH ASYMMETRIC HETEROGENEOUS PREFERENCES

1) CHANGE OF WHOLESALE PRICE WITH ASYMMETRIC HETEROGENEOUS PREFERENCES

From the above theoretic analysis, the wholesale price under asymmetric preferences in (8) and that under symmetric preferences in (20) can been attained with actual data respectively. Then, the sensitivity of wholesale price with respect

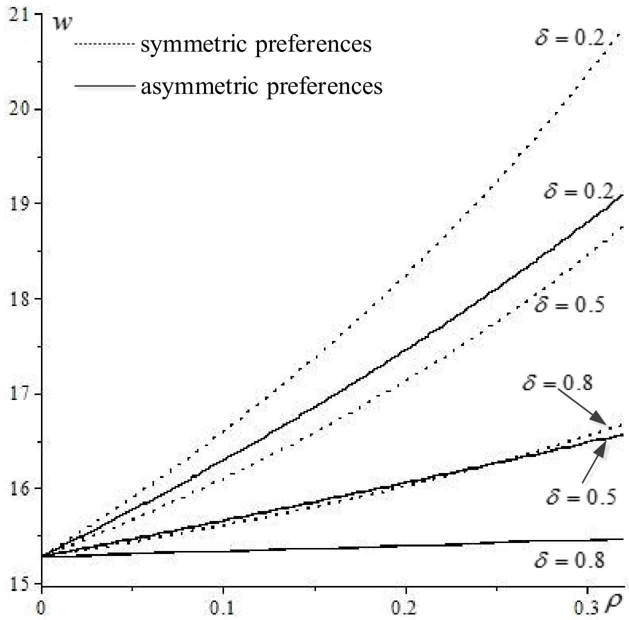

FIGURE 5. Change of wholesale price with asymmetric heterogeneous preferences.

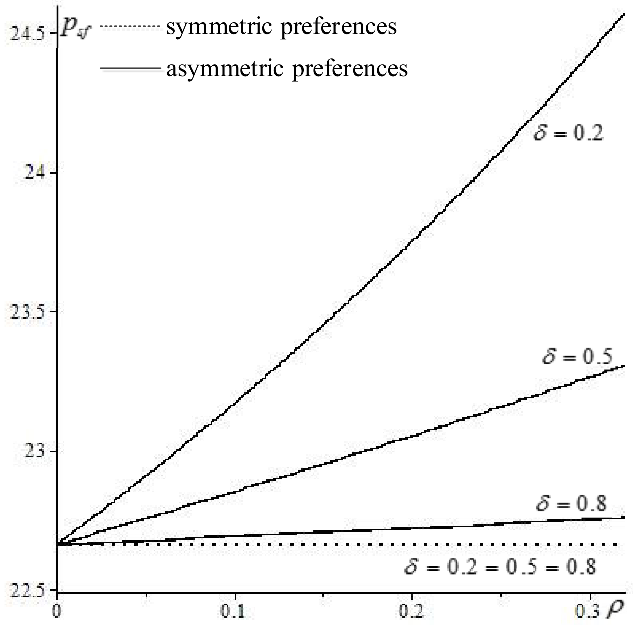

FIGURE 6. Change of self-interest retail price with asymmetric heterogeneous preferences.

to heterogeneous preferences is illustrated in figure 5, where the altruistic probability is remarked by 0.2 ($\delta = 0.8$), 0.5 ($\delta = 0.5$) and 0.8 ($\delta = 0.2$) directly and separately, the abscissa axis denotes the heterogeneity of preferences, the ordinate axis denotes the wholesale price, and results under symmetric and asymmetric information are denoted as dotted and solid line respectively.

In accordance with proposition 2, the wholesale price under asymmetric preferences is always lower than that under symmetric preferences. The difference increases in the heterogeneity of preferences, which illustrates proposition 6.

Furthermore, the wholesale price under asymmetric preferences increases monotonically in the heterogeneity of preferences in a nearly liner way, while that under symmetric preferences monotonically increases in a slow and nearly exponential way. Although both the increasing rates raise in the altruistic probability, the former is always smaller. Especially, when altruistic probability equals 0.2 ($\delta = 0.8$), the wholesale price under asymmetric preferences hardly increases in the heterogeneity of preferences, while that under symmetric preferences increases in a nearly linear way slowly. Additionally, as a pure coincidence, the wholesale price in the case of altruistic probability 0.5 ($\delta = 0.5$) under asymmetric preferences is almost the same as that in case of 0.2 ($\delta = 0.8$) under symmetric preferences. The difference between those under symmetric and asymmetric preferences increases in the heterogeneity of preferences and the altruistic probability, which represents the asymmetry of preferences. Consequently, an observation extending proposition 2 and 6 can be found as follows.

Observation 2: The influence extent of asymmetric preferences on wholesale price increases and accelerates in both the heterogeneity and asymmetry of preferences.

2) CHANGE OF RETAIL PRICE WITH ASYMMETRIC HETEROGENEOUS PREFERENCES

First, regarding self-interest retail price.

The retail price decided by the self-interest retailer under asymmetric preferences is attained in (9), while that under symmetric preferences is shown in (21). Then, the sensitivity of the self-interest retail price with respect to heterogeneous preferences is illustrated in figure 6, where the altruistic probability is remarked by 0.2 ($\delta = 0.8$), 0.5 ($\delta = 0.5$), and 0.8 ($\delta = 0.2$) directly and separately, the abscissa axis denotes the heterogeneity of preferences, the ordinate axis denotes the self-interest retail price, and results under symmetric and asymmetric preferences are denoted as dotted and solid line respectively. Especially, in case of symmetric preferences, the manufacturer knows surely the behavioral type of the retailer, and only the self-interest retailer decides the self-interest retail price, which thereby doesn't change with altruistic probability.

The self-interest retail price under asymmetric preferences is higher than that under symmetric preferences, which is in accordance with proposition 3. As proposition 7 shows, the difference between those under asymmetric and symmetric preferences increases in the heterogeneity of preferences. Besides, it also increases in the altruistic probability, which isn't included in the above theoretic findings.

Moreover, the self-interest retail price under symmetric preferences is irrelevant with heterogeneous preferences, while that under asymmetric preferences monotonically increases with a nearly linear way, where the increasing rate raises rapidly as the altruistic probability expands. Especially, when the altruistic probability equals 0.2 ($\delta = 0.8$), it hardly increases in the heterogeneity of preferences. Specifically, under asymmetric preferences, the self-interest retail price is influenced by the behavioral preference of the altruistic retailer affirmatively although she is purely self-interest herself, which is defined as unselfish intervening effect. As the altruistic probability grows, the unselfish intervening effect becomes stronger. When the altruistic probability equals 0.2 ($\delta = 0.8$) the unselfish intervening effect almost approaches the limit 0, while it appears very remarkable when the altruistic probability equals 0.8 ($\delta = 0.2$). Consequently, an observation is concluded as follows, which extends proposition 3 and 7 and describes the unselfish intervening effect on the self-interest retail price.

Observation 3: Asymmetric preferences results in unselfish intervening effect on the self-interest retail price, which pushes the influence extent of asymmetric preferences on self-interest retail price to increase in the heterogeneity and asymmetry of preferences.

Second, regarding the altruistic retail price.

The retail price decided by the altruistic retailer under asymmetric preferences is attained in the above (10), while that under symmetric preferences is shown in the above (22). Then, the sensitivity of the altruistic retail price with respect to heterogeneous preferences is illustrated in figure 7, where the altruistic probability is remarked by 0.2 ($\delta = 0.8$), 0.5 ($\delta = 0.5$), and 0.8 ($\delta = 0.2$) directly and separately, the abscissa axis denotes the heterogeneity of preferences, and the ordinate axis denotes the altruistic retail price, and results under symmetric and asymmetric preferences respectively are denoted as dotted and solid line. Especially, under symmetric preferences, the manufacturer knows surely the behavioral type of the retailer. Only the altruistic retailer decides the altruistic retail price, which thereby doesn't change with altruistic probability. It is similar to the self-interest retail price under symmetric preferences shown in figure 6.

It is clear that the altruistic retail price under asymmetric preferences is always lower than that under asymmetric preferences, which is in accordance with proposition 3. Moreover, the difference between those under asymmetric and symmetric preferences increases in the heterogeneity of preferences, which is consistent with proposition 7.

Furthermore, the altruistic retail price under asymmetric preferences decreases in heterogeneous preferences in a nearly linear way monotonically. Similar to the case of self-interest retail price, the decreasing rate monotonically increases in altruistic probability. The unselfish intervening effect is more remarkable because when the altruistic probability equals 0.2 ($\delta = 0.8$) the altruistic retail price under asymmetric preferences is greatly different from that under symmetric preferences. Consequently, an observation can been concluded as follows, which describes the unselfish intervening effect on the altruistic retail price.

Observation 4: The unselfish intervening effect from asymmetric preferences makes the sensitivity of the altruistic retail price with respect to heterogeneous preferences to increase in the asymmetry of preferences.

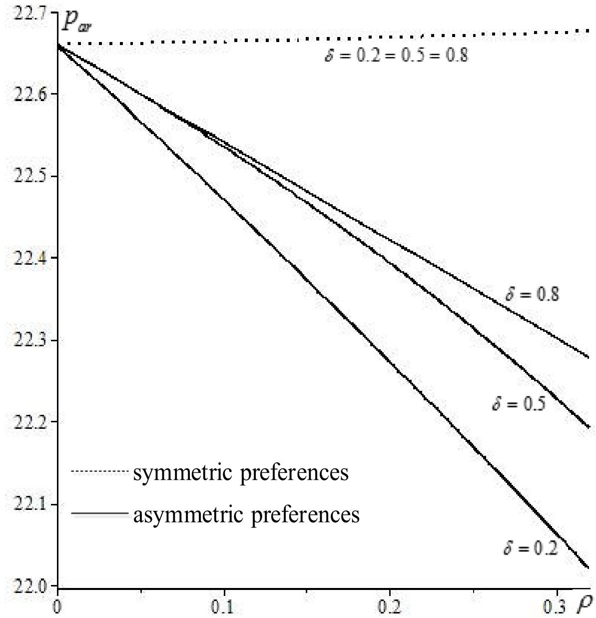

FIGURE 7. Change of altruistic retail price with asymmetric heterogeneous preferences.

Summarily, the case study reveals managerial implications for decision making of the supply chain. First, in perspective of upstream leader of the supply chain, the manufacturer should take asymmetric heterogeneous preferences into account when deciding the product greenness and wholesale price. Asymmetric preferences will surely reduce the product greenness and wholesale price, whose extents both increase in heterogeneous preferences. Second, in perspective of downstream follower of the supply chain, the retailer also should incorporate asymmetric heterogeneous preferences into the decision making of the retail price. Asymmetric preferences will enhance the retail price decided by the self-interest retailer while reduce that decided by the altruistic retailer, whose extents increase in heterogeneous preferences. The stronger heterogeneity and asymmetry of preferences, the more necessary to incorporate asymmetric heterogeneous preferences into decision making of the supply chain system.

VIII. CONCLUSION

A. CONCLUDING REMARKS

Developing a green supply chain can promote environmental protection, whose operational efficiency depends on product greenness and pricing strategy. Behavioral preferences such as altruism and fairness are important factors with a heavy impact on the decision making of product greenness and price of the supply chain. However, previous literature has been adopting the assumption of public and symmetric preferences, which contradicts the fact of diverse behaviors. For example, some behave in a self-interest way to maximize economic profit, while others take an altruistic approach to pursue reciprocal cooperation. Aiming at the contradiction between previous literature and the reality of actual diverse behaviors, this paper introduces asymmetric heterogeneous preferences to explore how asymmetric preferences affect the product greenness and pricing strategy of the supply chain, and analyze how the impact of asymmetric preferences changes with heterogeneous preferences. The theoretical framework and findings are general and universal because the same method can be applied to various preferences, such as fairness, reciprocity, jealousy, status-seeking, and so on. The main findings can be concluded as the following.

First, asymmetric preferences will reduce the product greenness, and its influence extent increases in heterogeneous preferences. However, previous literature has been holding that altruistic preference can enhance the product greenness. Actually, altruistic preferences really enhance the product greenness, but the asymmetric information of preferences reduces. The latter is the dominating power, by which altruistic preference will decrease instead of increase the product greenness under asymmetric preferences. So, the complete rational statement about the impact of altruistic preference on product greenness should be that altruistic preference will decrease product greenness under asymmetric preferences, but increase product greenness under symmetric preferences. Therefore, the above finding implements and corrects the universal conclusion of previous literature.

Second, asymmetric preferences will reduce the wholesale price, and its influence extent also increases in heterogeneous preferences. However, previous literature has been holding that altruistic preference can enhance the wholesale price. Actually, for individuals, in case of asymmetric preferences, altruistic preference will increase the wholesale price to the self-interest retailer, but decrease that to the altruistic retailer. The latter dominates the former, which results in the outcome that on the whole the wholesale price will be reduced by altruistic preference, instead of improvement in previous literature. Consequently, it also implements and corrects the common conclusion of previous literature.

Finally, asymmetric preferences will enhance the self-interest retail price, while reduce the altruistic retail price, and their influence extents both increase in heterogeneous preferences. However, previous literature neither considered asymmetric heterogeneous preferences, nor distinguished the influence direction determined by asymmetric preferences and the influence extent determined by heterogeneous preferences. Specifically, this paper found that the influence direction is definitely up to the asymmetry of preferences and thereby depends on the behavioral type of the retailer, while the influence extent is surely up to the heterogeneity of preferences and thereby doesn't depend on the behavioral type of the retailer. In this sense, the above finding actually is a new issue that has never been touched in previous literature.

B. MANAGERIAL IMPLICATIONS

Some managerial implications for managers of supply chain, especially how to decide optimal product greenness and pricing strategy, can be concluded from the above findings.

First, it is necessary for managers to incorporate properly asymmetric heterogeneous preferences, which can ensure rational decision making of product greenness and pricing strategy. The traditional self-interest preference will result in decision bias because the unselfish behaviors such as altruism and fairness are also popular and affect economic behaviors in a different way, which has been proven by many experimental and empirical researches in behavioral economics. Furthermore, the widely adopted assumption of public and symmetric preferences in previous supply chain literature also will lead to decision bias because the behavior types aren't public information actually. Then, asymmetric heterogeneous preferences will influence heavily the decision making of product greenness and price. Specifically, the influence direction is determined by the asymmetry of preferences, while the influence extent is up to the heterogeneity of preferences. Summarily, only under the realistic condition of asymmetric heterogeneous preferences, the product greenness and price can been decided reasonably.

Second, it is necessary for managers to adjust estimation about the behavior types of supply chain partners promptly, which can facilitate precise dynamic decision making of product greenness and pricing strategy. The estimation of possible types, strengths, and their probability distribution of supply chain partners' preferences is the precondition of decision making. Precise estimation can ensure rational decision, and prompt adjustment, namely, the promptly updating information about the usual market demand, the behavioral style of supply chain partners, and so on, can promote the estimation to change in time correspondingly, and thereby can make a dynamic rational decision. So, smart information management, especially those on behavioral style information of supply chain partners, comprehensive integration of the direct relevant information collected oneself, and the indirect information from third parties such as banks and professional consulting agencies, actually is useful for supply chain management. Moreover, the dynamic rational decision of product greenness and pricing strategy is in favor of the successive transmission, gradual optimization, and positive emission reduction of the supply chain. The improvement of the accuracy of the prediction can not only enhance the precision of decision making but also reduce the loss from asymmetric information of behavioral preferences.

Finally, it is necessary for managers to adopt blockchain technology into the supply chain management, which can alleviate the asymmetric degree of heterogeneous preferences and thereby advance precise decision making of product greenness and pricing strategy. Under realistic asymmetric heterogeneous preferences, the concrete types and strengths of the behavioral preferences are actually a kind of private and asymmetric information. Supply chain partners may lie and feign behavioral types and strengths, which may make the asymmetry of heterogeneous preferences more serious. The blockchain technology can ensure that all information can't been changed in any way once it is stored. Therefore, it can promote the elimination of falsehood and guise, and improve the accuracy of the prediction on behavioral types and strengths. Although it will require some costs, adoption of blockchain technology can eliminate the operational losses from information asymmetry, which usually are bigger than the required costs in long run.

APPENDIX

A. PROOF OF PROPOSITION 1

First, from $\bar{e}^* = \frac{\theta(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $E(e^*) = \frac{\theta(a-c)[4k(1-\delta\rho)-\theta^2]}{(4k-\theta^2)[4k(1-\rho)-\theta^2]}$, yields $E(e^*) - \bar{e}^* = \frac{4\theta\delta k\rho(1-\delta)(a-c)[4k(1-\delta\rho+\rho)-\theta^2]}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}[4k(1-\rho)-\theta^2](4k-\theta^2)}$, where $c < a$, $0 < \delta < 1$, $0 < \rho < 1$, and k is sufficiently large. Then, $\bar{e}^* < E(e^*)$ is proven.

Second, from $\bar{e}^* = \frac{\theta(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $e^*_{sf} = \frac{\theta(a-c)}{4k-\theta^2}$, yields $\bar{e}^* - e^*_{sf} = \frac{4\theta k\rho(a-c)(1-\delta)^2}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}(4k-\theta^2)}$, where $c < a$, $0 < \delta < 1, 0 < \rho < 1$, and k is sufficiently large. $e^*_{sf} < \bar{e}^*$ is proven.

Third, from $\bar{e}^* = \frac{\theta(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $e^*_{ar} = \frac{\theta(a-c)}{4k(1-\rho)-\theta^2}$, yields $e^*_{ar} - \bar{e}^* = \frac{4\theta\delta k\rho(2-\delta)(a-c)}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}[4k(1-\rho)-\theta^2]}$, where $c < a$, $0 < \delta < 1, 0 < \rho < 1$, and k is sufficiently large. Then, $\bar{e}^* < e^*_{ar}$ is proven.

Summing up the above three points, the proof is completed.

B. PROOF OF PROPOSITION 2

First, from $\bar{w}^* = c + \frac{2k(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $E(w^*) = c + \frac{2k(a-c)[4k(1-\delta\rho)-\theta^2]}{(4k-\theta^2)[4k(1-\rho)-\theta^2]}$, yields $E(w^*) - \bar{w}^* = \frac{8\delta k^2\rho(1-\delta)(a-c)[4k(1-\delta\rho+\rho)-\theta^2]}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}[4k(1-\rho)-\theta^2](4k-\theta^2)}$ where $c < a, 0 < \delta < 1, 0 < \rho < 1$, and k is sufficiently large. Then, $\bar{w}^* < E(w^*)$ is proven.

Second, from $\bar{w}^* = c + \frac{2k(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $w^*_{sf} = c + \frac{2k(a-c)}{4k-\theta^2}$, yields $\bar{w}^* - w^*_{sf} = \frac{8k^2\rho(1-\delta)^2(a-c)}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}(4k-\theta^2)}$ where $c < a$, $0 < \delta < 1$, $0 < \rho < 1$, and k is sufficiently large. Then,$w^*_{sf} < \bar{w}^*$ is proven.

Third, from $\bar{w}^* = c + \frac{2k(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $w^*_{ar} = c + \frac{2k(a-c)}{4k(1-\rho)-\theta^2}$, yields $w^*_{ar} - \bar{w}^* = \frac{8\delta k^2\rho(2-\delta)(a-c)}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}[4k(1-\rho)-\theta^2]}$ where $c < a$, $0 < \delta < 1$, $0 < \rho < 1$, and k is sufficiently large. Then, $\bar{w}^* < w^*_{ar}$ is proven.

Summing up the above three points, the proof is completed.

C. PROOF OF PROPOSITION 3

First, from $\bar{p}^*_{sf} = c + \frac{k(a-c)[1+2(1-\rho)+2\rho\delta(2-\delta)]}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $p^*_{sf} = c+\frac{3k(a-c)}{4k-\theta^2}$, yields $\bar{p}^*_{sf} - p^*_{sf} = \frac{2k\rho(1-\delta)^2(\theta^2+2k)(a-c)}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}(4k-\theta^2)}$ where $c < a$, $0 < \delta < 1$, $0 < \rho < 1$, and k is sufficiently large. Then, $\bar{p}^*_{sf} > p^*_{sf}$ is proven.

Second, from $\bar{p}^*_{ar} = c + \frac{k(a-c)[3(1-\rho)+\rho\delta(5-2\delta)]}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $p^*_{ar} = c + \frac{3k(a-c)(1-\rho)}{4k(1-\rho)-\theta^2}$, yields $p^*_{ar} - \bar{p}^*_{ar} = \frac{\delta k\rho(a-c)[4k(1-\rho)(1-\delta)+\theta^2(5-2\delta)]}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}[4k(1-\rho)-\theta^2]}$ where $c < a$, $0 < \delta < 1$, $0 < \rho < 1$, and k is sufficiently large. Then, $\bar{p}^*_{ar} < p^*_{ar}$ is proven.

Summing up the above two points, the proof is completed.

D. PROOF OF PROPOSITION 4

First, from $E(\bar{\pi}^*_m) = \frac{k(a-c)^2}{2\{4k[1-\rho(1-\delta)^2]-\theta^2\}}$ and $E(\pi^*_m) = \frac{k(a-c)^2[4k(1-\delta\rho)-\theta^2]}{2(4k-\theta^2)[4k(1-\rho)-\theta^2]}$, yields $E(\pi^*_m) - E(\bar{\pi}^*_m) = \frac{2\delta k^2\rho(a-c)^2(1-\delta)[4k(1+\rho-\rho\delta)-\theta^2]}{(4k-\theta^2)[4k(1-\rho)-\theta^2]\{4k[1-\rho(1-\delta)^2]-\theta^2\}}$ where $c < a, 0 < \delta < 1$, $0 < \rho < 1$, and k is sufficiently large. Then, $E(\bar{\pi}^*_m) < E(\pi^*_m)$ is proven.

Second, from $\bar{\pi}^*_{r-sf} = \frac{k^2(a-c)^2[1-2\rho(1-\delta)^2]^2}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2}$ and $\pi^*_{r-sf} = \frac{k^2(a-c)^2}{(4k-\theta^2)^2}$, yields $\bar{\pi}^*_{r-sf} - \pi^*_{r-sf} = 4k^2\rho(a-c)^2 \times \frac{(1-\delta)^2(2k-\theta^2)\{6k[\rho(1-\delta)^2-2/3]+\theta^2[1-\rho(1-\delta)^2]\}}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2(4k-\theta^2)^2}$ where $0 < \delta < 1$, $0 < \rho < 1$, and enough large k ensure $sign(\bar{\pi}^*_{r-sf} - \pi^*_{r-sf}) = sign[\rho(1-\delta)^2 - 2/3]$. It is clear that $\bar{\pi}^*_{r-sf} > \pi^*_{r-sf}$ only if $\rho(1-\delta)^2 - 2/3 > 0$. With the constraint $0 < \delta < 1$ and $0 < \rho < 1$, $\rho(1-\delta)^2 - 2/3 < 0$ requires both $0 < \delta < 1 - \sqrt{\frac{2}{3}}$ and $\frac{2}{3(1-\delta)^2} \leq \rho < 1$, which defines the domain A in figure 1. That is to say, in the domain B which illustrates most cases, $\bar{\pi}^*_{r-sf} < \pi^*_{r-sf}$, while in the domain A which denotes exception of few cases, $\bar{\pi}^*_{r-sf} > \pi^*_{r-sf}$. Then, $\bar{\pi}^*_{r-sf} < \pi^*_{r-sf}$ unless $\frac{2}{3(1-\delta)^2} \leq \rho < 1$ and $0 < \delta < 1 - \sqrt{\frac{2}{3}}$ is proven.

Third, from $\pi^*_{r-ar} = \frac{k^2(a-c)^2(1-3\rho)(1-\rho)}{[4k(1-\rho)-\theta^2]^2}$ and $\bar{\pi}^*_{r-ar} = \frac{k^2(a-c)^2[1+(1-\delta)(2\delta-3)\rho][1+(1-\delta)(2\delta-1)\rho]}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2}$ yields $\bar{\pi}^*_{r-ar} - \pi^*_{r-ar} = \frac{k^2\delta\rho(a-c)^2(\delta-2)X_1}{[4k(1-\rho)-\theta^2]^2\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2}$, where $X_1 = 16(\rho-1)[\rho(\rho-3)\delta^2 - 2\rho(\rho-3)\delta + (\rho^2 - 3\rho + 2)]k^2 + 8\theta^2(\rho-1)(4\rho\delta^2 - 8\delta\rho + 4\rho - 3)k + \theta^4(4\rho\delta^2 - 8\delta\rho + 7\rho - 4)$. Because of $0 < \rho < 1, 0 < \delta < 1$, and large enough k, it is easy to find that $sign(\bar{\pi}^*_{r-ar} - \pi^*_{r-ar}) = sign[\rho(\rho-3)\delta^2 - 2\rho(\rho-3)\delta + (\rho^2 - 3\rho + 2)]$. The roots of the equation $\rho(\rho-3)\delta^2 - 2\rho(\rho-3)\delta + (\rho^2 - 3\rho + 2) = 0$ are $\delta_1 = 1 + \frac{\sqrt{2}}{\sqrt{\rho(3-\rho)}} > 1$ and $\delta_2 = 1 - \frac{\sqrt{2}}{\sqrt{\rho(3-\rho)}} < 0$ respectively. From $0 < \delta < 1$ and $\rho(\rho-3) < 0$, yields $\rho(\rho-3)\delta^2 - 2\rho(\rho-3)\delta + (\rho^2 - 3\rho + 2) > 0$. Thus, $sign(\bar{\pi}^*_{r-ar} - \pi^*_{r-ar}) = 1$. Then, $\bar{\pi}^*_{r-ar} > \pi^*_{r-ar}$ is proven.

Finally, from $u^*_{r-ar} = \frac{k(a-c)^2[2k(1-\rho)^2-\theta^2\rho]}{2[4k(1-\rho)-\theta^2]^2}$ and $\bar{u}^*_{r-ar} = \frac{k(a-c)^2}{2\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2} \times \{2k(1-2\delta)^2(1-\delta)^2\rho^2 + [4k - 8k(1-\delta)^2 - \theta^2]\rho + 2k\}$, yields $\bar{u}^*_{r-ar} - u^*_{r-ar} = \frac{k^2\delta\rho(a-c)^2(\delta-2)X_2}{[4k(1-\rho)-\theta^2]^2\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2}$, where $X_2 = 16(\rho-1)^2[3\rho(1-\delta)^2 - 2]k^2 + 8\theta^2(5\delta^2\rho^2 - 4\delta^2\rho - 10\delta\rho^2 + 8\delta\rho + 6\rho^2 - 9\rho + 3)k + \theta^4(4\rho\delta^2 - 8\delta\rho + 9\rho - 4)$. From $0 < \rho < 1$, $0 < \delta < 1$, and sufficiently large k, it can be found that $sign(\bar{u}^*_{r-ar} - u^*_{r-ar}) = -sign[3\rho(1-\delta)^2 - 2]$. Then, $\bar{u}^*_{r-ar} > u^*_{r-ar}$ only if $3\rho(1-\delta)^2 - 2 < 0$. So, $\bar{u}^*_{r-ar} > u^*_{r-ar}$ unless $0 < \delta < 1 - \sqrt{\frac{2}{3}}$ and $\frac{2}{3(1-\delta)^2} \leq \rho < 1$ is proven.

Summing up the above four points, the proof is completed.

E. PROOF OF PROPOSITION 5

First, from $E(e^*) = \frac{\theta(a-c)[4k(1-\delta\rho)-\theta^2]}{(4k-\theta^2)[4k(1-\rho)-\theta^2]}$ and $\bar{e}^* = \frac{\theta(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2}$, yields $\frac{\partial[E(e^*)-\bar{e}^*]}{\partial\rho} = \frac{4\theta k\delta(1-\delta)(a-c)X_3}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2[4k(1-\rho)-\theta^2]^2}$, in which $X_3 = 16(\rho^2\delta^3 - 4\rho^2\delta^2+6\rho^2\delta-3\rho^2-2\rho\delta+2\rho+1)k^2+8(\rho\delta-\rho-1)\theta^2k+\theta^4$. From $c < a$, $0 < \delta < 1$, and large enough k, yields $sign\left\{\frac{\partial[E(e^*)-\bar{e}^*]}{\partial\rho}\right\} = sign(X_3)$ and $\rho^2\delta^3 - 4\rho^2\delta^2 + 6\rho^2\delta - 3\rho^2 - 2\rho\delta + 2\rho + 1 > 1$, namely $sign(X_3) = 1$. Therefore, $sign\left\{\frac{\partial[E(e^*)-\bar{e}^*]}{\partial\rho}\right\} = 1$. Then, $0 < \frac{\partial[E(e^*)-\bar{e}^*]}{\partial\rho}$ is proven.

Second, from $\bar{e}^* = \frac{\theta(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $e^*_{sf} = \frac{\theta(a-c)}{4k-\theta^2}$, yields $\frac{\partial(\bar{e}^*-e^*_{sf})}{\partial\rho} = \frac{4\theta k(a-c)(1-\delta)^2}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2}$, where $c < a$. Then, $\frac{\partial(\bar{e}^*-e^*_{sf})}{\partial\rho} > 0$ is proven.

Third, from $\bar{e}^* = \frac{\theta(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $e^*_{ar} = \frac{\theta(a-c)}{4k(1-\rho)-\theta^2}$, yields $\frac{\partial(e^*_{ar}-\bar{e}^*)}{\partial\rho} = \frac{4\theta\delta k(2-\delta)(a-c)}{[4k(1-\rho)-\theta^2]^2} \times \frac{[4k(1-\rho+\rho\delta)-\theta^2][4k(1+\rho-\rho\delta)-\theta^2]}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2}$ where $c < a$, $0 < \delta < 1$, $0 < \rho < 1$, and k is sufficiently large. Then, $\frac{\partial(e^*_{ar}-\bar{e}^*)}{\partial\rho} > 0$ is proven.

Summing up the above three points, the proof is completed.

F. PROOF OF PROPOSITION 6

First, from $\bar{w}^* = c + \frac{2k(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $E(w^*) = c + \frac{2k(a-c)[4k(1-\delta\rho)-\theta^2]}{(4k-\theta^2)[4k(1-\rho)-\theta^2]}$, yields $\frac{\partial[E(w^*)-\bar{w}^*]}{\partial\rho} = \frac{8k^2\delta(1-\delta)(a-c)X_4}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2[4k(1-\rho)-\theta^2]^2}$, where $X_4 = 16(\rho^2\delta^3 - 4\rho^2\delta^2+6\rho^2\delta-3\rho^2-2\rho\delta+2\rho+1)k^2+8(\rho\delta-\rho-1)\theta^2k+\theta^4$. From $c < a$, $0 < \delta < 1$, and enough large k, yields $sign\left\{\frac{\partial[E(w^*)-\bar{w}^*]}{\partial\rho}\right\} = sign(X_4)$ and $\rho^2\delta^3 - 4\rho^2\delta^2 + 6\rho^2\delta - 3\rho^2 - 2\rho\delta + 2\rho + 1 > 1$, namely $sign(X_4) = 1$. Therefore, $sign\left\{\frac{\partial[E(w^*)-\bar{w}^*]}{\partial\rho}\right\} = 1$. Then, $0 < \frac{\partial[E(w^*)-\bar{w}^*]}{\partial\rho}$ is proven.

Second, from $\bar{w}^* = c + \frac{2k(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $w^*_{ar} = c + \frac{2k(a-c)}{4k(1-\rho)-\theta^2}$, yields $\frac{\partial[w^*_{ar}-\bar{w}^*]}{\partial\rho} = \frac{8\delta k^2(a-c)}{[4k(1-\rho)-\theta^2]^2} \times \frac{(2-\delta)[4k(1-\rho+\rho\delta)-\theta^2][4k(1+\rho-\rho\delta)-\theta^2]}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2}$, where $c < a$, $0 < \delta < 1$, $0 < \rho < 1$, and k is sufficiently large. Then, $\frac{\partial[w^*_{ar}-\bar{w}^*]}{\partial\rho} > 0$ is proven.

Finally, from $\bar{w}^* = c + \frac{2k(a-c)}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $w^*_{sf} = c + \frac{2k(a-c)}{4k-\theta^2}$, yields $\frac{\partial(\bar{w}^*-w^*_{sf})}{\partial\rho} = \frac{8k^2(1-\delta)^2(a-c)}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2}$, where $c < a$. Then, $\frac{\partial(\bar{w}^*-w^*_{sf})}{\partial\rho} > 0$ is proven.

Summing up the above three points, the proof is completed.

G. PROOF OF PROPOSITION 7

First, from $\bar{p}^*_{sf} = c + \frac{k(a-c)[1+2(1-\rho)+2\rho\delta(2-\delta)]}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $p^*_{sf} = c + \frac{3k(a-c)}{4k-\theta^2}$, yields $\frac{\partial(\bar{p}^*_{sf}-p^*_{sf})}{\partial\rho} = 2k(1-\delta)^2 \times \frac{(\theta^2+2k)(a-c)}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2}$, where $c < a$. Then, $\frac{\partial(\bar{p}^*_{sf}-p^*_{sf})}{\partial\rho} > 0$ is proven.

Second, from $\bar{p}^*_{ar} = c + \frac{k(a-c)[3(1-\rho)+\rho\delta(5-2\delta)]}{4k[1-\rho(1-\delta)^2]-\theta^2}$ and $p^*_{ar} = c + \frac{3k(a-c)(1-\rho)}{4k(1-\rho)-\theta^2}$, yields $\frac{\partial(p^*_{ar}-\bar{p}^*_{ar})}{\partial\rho} = \frac{k\delta(a-c)X_5}{(4k\rho+\theta^2-4k)^2(4\delta^2k\rho-8k\rho\delta+4k\rho+\theta^2-4k)^2}$, where $X_5 = 64(1-\rho)^2(1-\delta)k^3+16\theta^2(3\delta^3\rho^2-12\delta^2\rho^2+16\delta\rho^2-4\delta\rho-7\rho^2+4\rho+3)k^2+4\theta^4(2\delta\rho+3\delta-2\rho-9)k-\theta^6(2\delta-5)$. From $c < a$, enough large$k$, and $0 < \delta < 1$, yields $sign\left[\frac{\partial(p^*_{ar}-\bar{p}^*_{ar})}{\partial\rho}\right] = sign[64(1-\rho)^2(1-\delta)] = 1$. Then, $\frac{\partial(p^*_{ar}-\bar{p}^*_{ar})}{\partial\rho} > 0$ is proven.

Summing up the above two points, the proof is completed.

H. PROOF OF PROPOSITION 8

First, from $E(\bar{\pi}^*_m) = \frac{k(a-c)^2}{2\{4k[1-\rho(1-\delta)^2]-\theta^2\}}$ and $E(\pi^*_m) = \frac{k(a-c)^2[4k(1-\delta\rho)-\theta^2]}{2(4k-\theta^2)[4k(1-\rho)-\theta^2]}$, yields $\frac{\partial[E(\pi^*_m)-E(\bar{\pi}^*_m)]}{\partial\rho} = \frac{2k^2\delta(1-\delta)(a-c)^2}{[4k(1-\rho)-\theta^2]^2\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2} \times [16(\delta^3\rho^2-4\delta^2\rho^2+6\delta\rho^2-2\rho\delta-3\rho^2+2\rho+1)k^2+8\theta^2(\delta\rho-\rho-1)k+\theta^4]$. It is clear that $sign\left\{\frac{\partial[E(\pi^*_m)-E(\bar{\pi}^*_m)]}{\partial\rho}\right\} = sign(\delta^3\rho^2 - 4\delta^2\rho^2 +6\delta\rho^2 - 2\rho\delta - 3\rho^2 + 2\rho + 1)$ because of $0 < \delta < 1$ and sufficiently large k. From $0 < \delta < 1$ and $0 < \rho < 1$, it can be attained that $\rho^2\delta^3 - 4\rho^2\delta^2+6\rho^2\delta-3\rho^2-2\rho\delta+2\rho+1 > 1$. Then, yields $sign\left\{\frac{\partial[E(\pi^*_m)-E(\bar{\pi}^*_m)]}{\partial\rho}\right\} = 1$, which can prove $\frac{\partial[E(\pi^*_m)-E(\bar{\pi}^*_m)]}{\partial\rho} > 0$.

Second, from $\bar{\pi}^*_{r-sf} = \frac{k^2(a-c)^2[1-2\rho(1-\delta)^2]^2}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2}$ and $\pi^*_{r-sf} = \frac{k^2(a-c)^2}{(4k-\theta^2)^2}$, yields $\frac{\partial(\pi^*_{r-sf}-\bar{\pi}^*_{r-sf})}{\partial\rho} = 8k^2(a-c)^2 \times \frac{[1/2-\rho(1-\delta)^2](1-\delta)^2(2k-\theta^2)}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^3}$. It can be attained that $sign\left[\frac{\partial(\pi^*_{r-sf}-\bar{\pi}^*_{r-sf})}{\partial\rho}\right] = sign[1/2-\rho(1-\delta)^2]$ because $0 < \delta < 1$, $0 < \rho < 1$, and k is sufficiently large. With the constraint $0 < \delta < 1$ and $0 < \rho < 1$, $1/2-\rho(1-\delta)^2 < 0$ requires both $\frac{1}{2(1-\delta)^2} < \rho < 1$ and $0 < \delta < 1-\sqrt{\frac{1}{2}}$, which defines the domain C in ifigure 2. That is to say, in the domain D which illustrates most cases, $0 < \frac{\partial(\pi^*_{r-sf}-\bar{\pi}^*_{r-sf})}{\partial\rho}$, while in the domain C which denotes exception of few cases, $\frac{\partial(\pi^*_{r-sf}-\bar{\pi}^*_{r-sf})}{\partial\rho} < 0$. Then, $0 < \frac{\partial(\pi^*_{r-sf}-\bar{\pi}^*_{r-sf})}{\partial\rho}$ unless $0 < \delta < 1-\sqrt{\frac{1}{2}}$ and $\frac{1}{2(1-\delta)^2} < \rho < 1$ is proven.

Third, from $\pi^*_{r-ar} = \frac{k^2(a-c)^2(1-3\rho)(1-\rho)}{[4k(1-\rho)-\theta^2]^2}$ and $\bar{\pi}^*_{r-ar} = \frac{k^2(a-c)^2[1+(1-\delta)(2\delta-3)\rho][1+(1-\delta)(2\delta-1)\rho]}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2}$, yields $\frac{\partial(\bar{\pi}^*_{r-ar}-\pi^*_{r-ar})}{\partial\rho} = -\frac{2k^2\delta(a-c)^2(2-\delta)}{\{4k[1-\rho(1-\delta)^2]-\theta^2\}^3} \times \frac{X_6}{[4k(1-\rho)-\theta^2]^3}$, where $X_6 = 256(\rho-1)(\delta^4\rho^3 - 4\delta^3\rho^3 + 5\delta^2\rho^3 + \delta^2\rho^2 - 2\delta\rho^3 - 2\delta^2\rho - 2\delta\rho^2 + 4\delta\rho + \rho^2 - 2\rho + 1)k^4 - 64\theta^2[(3\delta^2-6\delta+2(1-\delta)^2\rho^4 - 2(\delta^2-2\delta-1)(1-\delta)^2\rho^3 - 15(1-\delta)^2\rho^2 + 2\rho(5\delta^2-10\delta+8)-5]k^3 + 48\theta^4(\delta^2\rho^3 - 8\delta^2\rho^2 - 2\delta\rho^3 + 6\delta^2\rho + 16\delta\rho^2 + \rho^3 - 12\delta\rho - 8\rho^2 + 10\rho - 3)k^2 + 4\theta^6(12\delta^2\rho^2 - 14\delta^2\rho - 24\delta\rho^2 + 28\delta\rho + 12\rho^2 - 24\rho + 7)k + \theta^8(4\delta^2\rho - 8\delta\rho + 7\rho - 2)$. From $0 < \rho < 1$, $0 < \delta < 1$, and sufficiently large k, it is clear that$sign\left[\frac{\partial(\bar{\pi}^*_{r-ar}-\pi^*_{r-ar})}{\partial\rho}\right] = -sign(X_6) = sign[g(\delta,\rho)] = 1$, where $g(\delta,\rho) = \delta^4\rho^3 - 4\delta^3\rho^3 + 5\delta^2\rho^3 + \delta^2\rho^2 - 2\delta\rho^3 - 2\delta^2\rho - 2\delta\rho^2 + 4\delta\rho + \rho^2 - 2\rho + 1 = \delta\rho(\delta-2)[\delta\rho^2(\delta-2) + (\rho^2-1) + (\rho-1)] + (\rho-1)^2 > 0$, which proves $\frac{\partial(\bar{\pi}^*_{r-ar}-\pi^*_{r-ar})}{\partial\rho} > 0$.

Finally, from $u^*_{r-ar} = \frac{k(a-c)^2[2k(1-\rho)^2-\theta^2\rho]}{2[4k(1-\rho)-\theta^2]^2}$ and $\bar{u}^*_{r-ar} = \frac{k(a-c)^2}{2\{4k[1-\rho(1-\delta)^2]-\theta^2\}^2} \times \{2k(4\delta^2 - 8\delta + 1)(1-\delta)^2\rho^2 + [4k - 8k(1-\delta)^2 - \theta^2]\rho + 2k\}$, yields $\frac{\partial(\bar{u}^*_{r-ar}-u^*_{r-ar})}{\partial\rho} = \frac{-2k^2\delta(a-c)^2(2-\delta)X_7}{[4k(1-\rho)-\theta^2]^3\{4k[1-\rho(1-\delta)^2]-\theta^2\}^3}$, where $X_7 = 4096(1-\rho)(1-\delta)^2[4\rho(1-\delta)^2-1]k^6 + \cdots$. From $0 < \rho < 1$, $0 < \delta < 1$, and sufficiently large k, yields $sign\left[\frac{\partial(\bar{u}^*_{r-ar}-u^*_{r-ar})}{\partial\rho}\right] = -sign(X_7) = -sign[4\rho(1-\delta)^2-1]$. Under constraint $0 < \delta < 1$ and $0 < \rho < 1$, $4\rho(1-\delta)^2 - 1 > 0$ requires both $\frac{1}{4(1-\delta)^2} < \rho < 1$ and $0 < \delta < \frac{1}{2}$, which defines the domain E in figure 3. Namely, in the domain F, which illustrates most cases, $\frac{\partial(\bar{u}^*_{r-ar}-u^*_{r-ar})}{\partial\rho} > 0$, while in the domain E, which denotes exception of few cases, $\frac{\partial(\bar{u}^*_{r-ar}-u^*_{r-ar})}{\partial\rho} < 0$.Thus, $\frac{\partial(\bar{u}^*_{r-ar}-u^*_{r-ar})}{\partial\rho} > 0$ unless $0 < \delta < \frac{1}{2}$ and $\frac{1}{4(1-\delta)^2} < \rho < 1$ is proven.

Summing up the above four points, the proof is completed.

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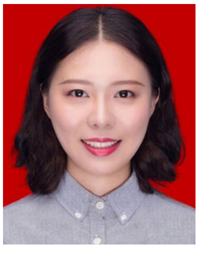

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