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Research Article

Research on Supply Chain Coordination and Profit Allocation Based on Altruistic Principal under Bilateral Asymmetric Information

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To ensure supply chain coordination and equitable profit allocation when there is bilateral asymmetric information, a supply chain consisting of one manufacturer with private manufacturing cost information and one retailer with private selling cost information is considered. A bilateral adverse selection model is established with a virtual altruistic principal as the coordination subject, for which the supply chain coordination conditions and an allocation rule for the supply chain surplus are then given. It was found that contract coordination depended on the costs and risk rates of both parties and market demand; that is, the lower the costs and the risk rate, the easier the supply chain coordination. Second, the trading volume distortion degree was positively correlated with production cost, sales cost, and price sensitivity and negatively correlated with the market environment parameter. Third, the allocation proportion for the supply chain surplus was determined. Finally, under a specific cost distribution assumption, a numerical example was given to simulate the contract execution and analyze the relationships between costs and profit.

1. Introduction

Enterprise competition now depends more on supply chain competition; consequently, the enterprise's goal is to ensure efficient supply chain management. However, the realization of this goal can be adversely affected by the asymmetric information between enterprises [1, 2]. For the manufacturer, because of the variety of raw materials and/or semifinished product procurement channels and the constantly changing production technology, production costs change frequently; therefore, only manufacturers are able to accurately know their own production costs. For retailers, because they have diverse distribution channels, there are varying sales costs; therefore, only retailers are able to accurately know their own sale costs. That is, the cost information at each node in the supply chain is asymmetric and generally confidential. Even within an enterprise, there is limited access to overall cost information. For competitors as well as consumers, when the cost information is available, their product price bottom line is also known, giving them the initiative in the pricing strategies game. However, enterprises with private information often seek to maximize their own profits rather than considering the benefits of the whole chain. Therefore, enterprises may intentionally conceal or falsely report information in an attempt to gain higher benefits or occupy the leading position in negotiations. The mutual influence of the false information between the two sides, however, could lead to a deviation from the individual target and system goal, thereby reducing supply chain efficiency.

To maximize overall supply chain profit, it is essential to establish appropriate internal incentive mechanisms in the supply chain. In the current design for supply chain incentive mechanisms, the principal's profit maximization is always taken as the goal; that is, the agent only receives basic reservation profits or a small information rent, with the principal receiving the majority of the profits from the whole chain. This is because the principal has the bargaining power and can provide "accept or leave" contracts. For a supply chain system with strong suppliers and strong retailers, such as those for GREE, WAL-MART, Lenovo, or Jing Dong Mall, and in supply chain systems made up of the weak suppliers and weak retailers, as it is unclear which companies have the absolute bargaining power over the supply chain, it is also unsure which enterprise is to provide the incentive contracts. However, as supply chain enterprises still have hidden information, the general principal-agent model is unable to effectively motivate them.

Although supply chain members understand that fully cooperating with other member enterprises can improve supply chain profits, it is very difficult to achieve. However, as a part of the supply chain, manufacturers and retailers are willing to cooperate in order to obtain greater profits. Therefore, this paper proposes cooperative contracts, for which profits are allocated after the cooperation has been completed. To improve supply chain efficiency, because there is bilateral asymmetric cost information and no incentive subject, an incentive subject called the altruistic principal is included in the incentive coordination mechanism to encourage coordinated supply chain management, which avoids the need for a supply chain partner to be the decision-maker. The altruistic principal here does not gain profit or generate cost, and the contract design reflects the willingness of the two parties to cooperate in the supply chain as they negotiate the contract from the supply chain view. The altruistic principal only provides the supply chain coordination mechanism embodied in the contract.

The remainder of this paper is structured as follows. Section 2 reviews the literature, in Section 3, the assumptions and notations are presented, and in Section 4, the coordinating contract with bilateral asymmetric information is developed and its efficiency examined. Section 5 provides numerical examples to illustrate the main results; and Section 6 concludes the paper and presents directions for future research. Proofs are presented in the appendices.

2. Literature Review

Technically, AI, big data, cloud computing, and block chain technology can alleviate the problem of information asymmetry between enterprises. Nakasumi (2017) [3] proposed a block chain based solution to address the problems of supply chain such as Double Marginalization and Information Asymmetry etc. In Lan et al. (2017) [4], the sales cost and the retailer's private information were mined by the manufacturer via advanced learning algorithms and related big data techniques. Sapuan et al. (2016) [5] used the latest technique from artificial intelligence system, i.e., a GA, to attain an optimal value for PSR and social learning process.

The research closely related to this paper is to solve and alleviate the information asymmetry between enterprises from the perspective of contract. The adverse selection and moral hazard models for asymmetric information developed by Affton and Martimort laid the foundation for research into incentive contract mechanisms under asymmetric information, after there was increased research focus on coordinated supply chain contracts with unilateral asymmetric information [6–10]. Zhao et al. (2014) [11] discussed the problem of adverse selection in a new kind of cooperative organization. The game model was built based on motivation theory and the principle-agent theory and then proved by examples. Guo et al. (2018) [12] established a supply chain contract by using a dynamic, Nash bargaining game to determine the optimal bargaining power allocation for the manufacturer, retailer, and society in an environment affected by moral hazard and irreversible investment. With three different information structures, full information, hidden actions, and hidden savings, Liu et al. (2018) [13] studied how to design an optimal contract which provides incentives for agent to put forth the desired effort in a continuous time dynamic moral hazard model with linear marginal productivity. These researches were generally based on agents with private information, thus allowing the principal to distinguish the agent's category or to motivate the agent through contract design.

Some scholars also studied single-sided double asymmetric information supply chains. Based on the principal-agent theory and with unknown information about the recycler's recycling capacity and recycling effort, Wang et al. (2016) [14] designed a contract to encourage the recycler to reveal their recycling capacity and improve the degree of effort after the contract signing. Li et al. (2016) [15] also studied supply chain incentives for the dual asymmetric information of private information for recycling and recovery efforts. Unlike Wang et al. (2016) [14] in which the recovery capability was discrete, Li et al. (2016) [15] assumed that the recycling capacity was continuous. The manufacturer provided a linear revenue sharing contract to the recyclers based on the observed recovery and system returns. Under the assumption that the seller's real inventory costs and sales effort information were asymmetrical, Wang et al. (2017) [16] studied a supply chain credit incentive problem, in which the manufacturer, as the principal, provided the seller with an incentive contract for the term of the credit and transfer payments.

Compared with single-sided asymmetric information, there has been less research on bilateral asymmetric information. Zhang et al. (2011) [17] developed a manufacturer led incentive model to determine the best profit sharing contract with the aim of reducing the two-way moral hazard. Corbett et al. (2005) [18] studied a two-way moral hazard problem when the effort on both sides of the supply chain reduced product consumption and proved that a revenue sharing contract was able to achieve both incentives as well as improving supply chain profit. Hahira (2014) [19] used a risk sharing contract to suppress the negative effects of the two-way moral hazard. Under the assumption of seller risk aversion and bilateral moral hazard, Dai et al. (2013) [20] and Fan et al. (2016) [21] investigated the ordering and promotion decisions of the suppliers and distributors' joint promotions for Newsboy products. With the supplier as the principal, the revenue sharing and buyback contract coordination was studied. To solve a bilateral moral hazard problem in the recycling of waste products, using the principal-agent theory with the manufacturer as principal, Hu et al. (2012) [22]

designed a linear contract based on a bilateral moral hazard that introduced an effort elasticity coefficient. Li et al. (2005) [23] and Li (2005) [24] also studied the bilateral moral risks in a supply chain based on the principal-agent theory.

Babaioff and Walsh (2005) [25] studied the problem of commodity trading in a supply chain using a bilateral auction mechanism and then designed a transfer payment based on Vickrey-Clarke-Groves to achieve higher supply chain efficiency under a negotiation mechanism. Zhang and Luo (2009) [26] assumed the seller's capital constraints and the manufacturer's capital costs were bilateral asymmetric information and, using a bilateral auction model, determined the relationship between the credit period length and the market power and information structure of both sides. Ma et al. (2009) [27] studied the design of a supply chain coordination mechanism under a private information condition based on the supplier's marginal costs and the retailer's processing costs and weakened the adverse selection problem caused by information asymmetry by introducing an information intermediary.

The above unilateral and bilateral asymmetric information research, whether based on the classic principal-agent theory or an auction mechanism, were based on the assumption that individual interests drove the decision-making rather than the interests of the whole supply chain. When both sides have private information, both parties seek to maximize their own interests rather than the interests of the supply chain system. Therefore, taking the supply chain as the incentive subject could be a solution [28, 29]; however, it has little practical significance. To resolve this problem, some scholars have applied the altruistic principal proposed by Fudenberg and Tirole (2005) [30] to supply chain contract designs for bilateral asymmetric information. Huang et al. (2013) [31] and Huang and Wang (2013) [32] developed two incentive models with no incentive subjects, in which the transfer payment was a function of the unobservable variables, which resulted in unenforceable contracts. Cheng et al.(2016) [33] considered the manufacturer's product costs as private information and the seller's sales efforts as private information to establish a two-way incentive model combined with an altruistic principal and then gave supply chain coordination conditions. Wang et al. (2012) [34] considered a supply chain with one supplier with private cost information and one retailer with private price information to develop a bilateral asymmetric information model using the altruistic principal, for which one allocation rule based on information rent was given. Zhang and Liu (2016) [35] developed a supply chain bilateral information asymmetry incentive model for one supplier with private cost information and one retailer with private demand information, with the altruistic principal being the system principal, in which a combination of order quantities and transfer payments was obtained to reveal both the manufacturer's and the seller's private information. Wang et al. (2017) [36] studied the supply chain contract for the supplier's production costs and the seller's evasion as the respective private information and revealed the conditions and influencing factors for supply chain coordination.

The above research examined different types of bilateral asymmetric information, such as production costs and sales efforts, production costs and sales prices, production costs and market demand, and production costs and the seller's risk aversion. The rapid development of production technology and the Internet have led to a gradual diversification of purchase and sales channels and a regular updating of production and sales technology, all of which has meant that production and sale costs change often; therefore, it is difficult for manufacturers and retailers to estimate each other's costs. Therefore, this paper sets the bilateral asymmetric information into the manufacturer's production costs and the retailer's sales costs.

Wang et al. (2013) [37] studied a supply chain composed of one manufacturer with private production costs and one retailer with private sales costs information. The incentive mechanism was established by introducing the AGV mechanism, and an allocation rule based on expected information rent was given. Based on trade volume and profit distribution rules, the transfer payments for the manufacturer and the seller were designed. On this basis, Wang (2015) [38] determined the retailer's risk aversion influence on information disclosure and coordination. However, the AGV mechanism requires that the agent's retained earnings be low enough [39, 40]; therefore, [37, 38] did not adequately account for the reservation profit for both parties. Further, the allocation rules in [37, 38] were based on the expected information rent, which was unrelated to the actual costs of the sales and marketing and also did not include the influence of the bargaining power of both parties. In addition, [37, 38] assumed that the sales price was exogenous. However, with improvements in the availability of consumer personal requirements, enterprises are inclined to provide more personalized products, so as to have some control over price; therefore, the sales price is not completely exogenous. Therefore, this paper overcomes the shortcomings in these papers by considering the reservation profit, bargaining power, and price control abilities of the two parties.

Based on the above analysis, in this paper, to account for the private cost information of both sides, an altruistic principal is introduced as the incentive subject to solve a two-way asymmetric problem that lacks an incentive subject, and a bilateral reverse selection mechanism is designed to reveal the bilateral cost information and improve supply chain efficiency. First, the supply chain integration decision profit is taken as the benchmark, after which a bilateral adverse selection model is established by introducing the altruistic principal as the incentive subject, and the conditions for the supply chain coordination under bilateral asymmetric information and the corresponding three regions are given. Then, depending on the reservation profits for both sides, the scope of the allocation proportion for the supply chain surplus is derived and converted into a transfer payment. Finally, the conclusions of the article and the contract implementation are illustrated in a numerical simulation.

3. Assumptions and Notations

Consider a two-firm supply chain consisting of one manufacturer and one retailer. The manufacturer sells the product

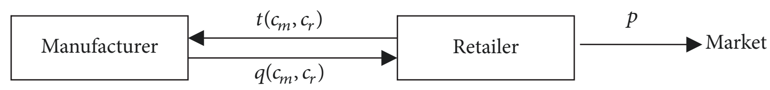

Figure 1: Supply chain structure.

through the retailer to the final market, and both the manufacturer and the retailer are risk neutral. The supply chain structure is shown in Figure 1. The arrow indicates the direction of the logistics and the flow of funds. Suppose $q(c_m, c_r)$ is the trading amount between the two parties that is the quantity of the retailer's order. Suppose $t(c_m, c_r)$ is the retailer's transfer payment to the manufacturer. The market demand function is $p = a - bq$ ($a > 0$, $b > 0$), in which p is the sales price (let $p \geq c_m + c_r$), q is the retailer's quantity demanded (it is assumed that the retailer's quantity demanded is the retailer's order and trading volume and there is no other channel for the retailer), a indicates the highest market price that consumers can accept, and $1/b$ represents the price sensitivity. The manufacturer's unit production cost c_m is private information, and the retailer knows the cost distribution based on the cost data from the manufacturer's industry. The cost c_m is distributed on the interval $[c_{m1}, c_{m2}]$, with the distribution function and density function being $F_1(c_m)$ and $f_1(c_m)$. The retailer's unit sales cost c_r is private information, and the manufacturer knows the cost distribution based on the cost data from the retailer's industry. The cost c_r is distributed on the interval $[c_{r1}, c_{r2}]$, with the distribution and density functions being $F_2(c_r)$ and $f_2(c_r)$. As it is assumed that the distribution functions on both sides satisfy the monotonic risk rate, most common distributions, such as uniform distributions, normal distributions, and logarithmic distributions, can satisfy this condition.

As both sides of the supply chain have private cost information and there is no definite incentive subject, the two sides negotiate to determine the optimal transaction volume and transfer payments. Before drawing up the contract, the manufacturer and seller both know their own costs exactly, but only know the other party's cost distribution; therefore, the two sides develop an incentive menu $q^*(c_m, c_r)$ with the expectation of maximizing the supply chain profit and encouraging the true cost information to be revealed. Then, from the reported costs and $q^*(c_m, c_r)$, the supply chain profits, the bilateral rents, and the supply chain surplus after removing rents are determined, and then the supply chain surplus is reallocated from the reservation profits of both sides. Next, a set of transfer payment menus $t^*(c_m, c_r)$ is designed based on the distribution rules, and, in the final step, the contract menu $\{q^*(c_m, c_r), t^*(c_m, c_r)\}$ is drawn up. If both sides' profits are greater than the reservation profits, the two parties reach a trade, with the trading volume being $q^*(c_m, c_r)$ and the transfer payment being $t^*(c_m, c_r)$. If the profits are less than the reservation profits, there is no transaction between the two parties.

4. Incentive Contracts

The centralized decision problem of a supply chain under symmetric information is first considered to determine the coordination standard. Then, the supply chain incentive and coordination problem under asymmetric information is analyzed.

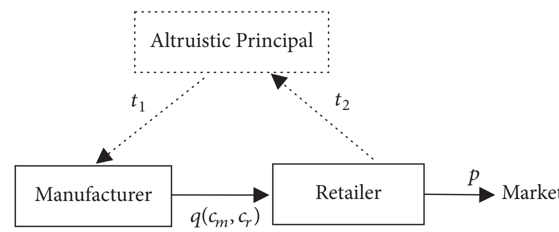

Figure 2: Supply chain structure with an altruistic principal.

4.1. Centralized Decision Model under Symmetric Information. Supply chain management has centralized decision-making if the manufacturer and retailer are the same decision-makers. Therefore, the total profit for the supply chain is as follows:

$$\left(p - c_m - c_r\right) q = \left(a - bq - c_m - c_r\right) q \tag{1}$$

From the first-order condition, the optimal trading amount for supply chain coordination can be determined.

$$q^c = \frac{a - c_m - c_r}{2b} \tag{2}$$

The total profit for the supply chain is

$$\Pi^c = \left(p^c - c_m - c_r\right) q^c = \frac{\left(a - c_m - c_r\right)^2}{4b}. \tag{3}$$

4.2. Bidirectional Incentive Model under Asymmetric Information. First, the incentive model is built and the optimal trading volume analyzed using model analysis. Then, the profit distribution is adjusted to determine the transfer payment that best satisfies the profit balance for the two sides.

4.2.1. Model Establishment. As shown in the dotted line in Figure 2, the altruistic principal gives consideration to the interests of all supply chain members and encourages both sides by maximizing expected supply chain revenue to determine the optimal volume q and the transfer payments t_1 and t_2. In Figure 2, t_1 is the manufacturer's revenue for providing q unit commodity and t_2 is the retailer's payment for the q unit commodity. As the principal is not an entity, they receive no income; that is, $t_1 = t_2 = t$.

As both parties have no knowledge about each other's cost information, they can only maximize their expected profits on the basis of the cost distribution function of the other side.

Therefore, the expected profits for c_m type manufacturer and c_r type retailer are as follows:

$$\Pi_m(c_m) = E_{c_r}\left[t_1(c_m, c_r) - c_m q(c_m, c_r)\right] \quad (4)$$

$$\Pi_r(c_r) = E_{c_m}\left[(p(c_m, c_r) - c_r) q(c_m, c_r) - t_2(c_m, c_r)\right] \quad (5)$$

The total expected supply chain profit is

$$\Pi = E_{c_m c_r}\left\{\left[p(c_m, c_r) - c_r - c_m\right] q(c_m, c_r)\right\} \quad (6)$$

Maximize the supply chain profit and establish the following program:

$$\begin{aligned}
\max_q \Pi = \max_q \quad & E_{c_m c_r}\left\{\left[p(c_m, c_r) - c_r - c_m\right] q(c_m, c_r)\right\} \\
\text{s.t} \quad & E_{c_r}\left[t_1(c_m, c_r) - c_m q(c_m, c_r)\right] \geq E_{c_r}\left[t_1(\tilde{c}_m, c_r) - c_m q(\tilde{c}_m, c_r)\right], \quad \forall c_m, \tilde{c}_m \in [c_{m1}, c_{m2}]
\end{aligned} \quad (7)$$

$$\begin{aligned}
& E_{c_m}\left[(p(c_m, c_r) - c_r) q(c_m, c_r) - t_2(c_m, c_r)\right] \geq E_{c_m}\left[(p(c_m, \tilde{c}_r) - c_r) q(c_m, \tilde{c}_r) - t_2(c_m, \tilde{c}_r)\right], \\
& \qquad \forall c_r, \tilde{c}_r \in [c_{r1}, c_{r2}]
\end{aligned} \quad (8)$$

$$\Pi_m(c_m) \geq \Pi_m^0 \quad (9)$$

$$\Pi_r(c_r) \geq \Pi_r^0 \quad (10)$$

$$t_1(c_m, c_r) = t_2(c_m, c_r) \quad (11)$$

where c_m, c_r are the real costs of the manufacturer and the retailer and $\tilde{c}_m$, $\tilde{c}_r$ are the reported costs of the manufacturer and the retailer. Conditions (7) and (8) are the incentive compatibility constraints for the manufacturer and retailer and indicate that the principal offers an incentive to the manufacturer and retailer to reveal their true information. Inequalities (9) and (10) are participation constraints, in which Π_m^0 and Π_r^0 are the reservation profits. For a menu to be accepted, it must yield to each type at an outside opportunity level, and because the principal is not an entity, the balance condition (11) must be satisfied.

4.2.2. Coordination Conditions. In this part, a new planning problem is derived by transforming the constraints in the above planning problems. After the analysis and solution, the supply chain coordination conditions and the optimal order quantities are determined. For article length reasons, the proofs for part of the lemmas and the conclusions can be found in the appendix.

Lemma 1. *Incentive compatibility constraints (7) and (8) can be reduced to the nonincreasing functions $E_{c_r}[q(c_m, c_r)]$ and $E_{c_m}[q(c_m, c_r)]$.*

Lemma 2. *The participation constraints (9) and (10) are equivalent to $\Pi_m(c_{m2}) = \Pi_m^0$ and $\Pi_r(c_{r2}) = \Pi_r^0$.*

Lemma 2 implies that only the most inefficient type of participation constraints can be binding.

Lemma 3 (Guo Hongmei. Research on supply chain contract and efficiency based on reverse selection model [M]. Chengdu: Sichuan University press, 2016.). *Information rents for a manufacturer with cost c_m and a retailer with cost c_r can be described as follows:*

$$\Pi_m(c_m) = \Pi_m^0 + \int_{c_m}^{c_{m2}} E_{c_r}\left[q(\tilde{c}_m, c_r)\right] d\tilde{c}_m \quad (12)$$

$$\Pi_r(c_r) = \Pi_r^0 + \int_{c_r}^{c_{r2}} E_{c_m}\left[q(c_m, \tilde{c}_r)\right] d\tilde{c}_r \quad (13)$$

Lemma 4. *If $q(c_m, c_r)$ is the solution to the following programming problem, as long as $E_{c_r}[q(c_m, c_r)]$ and $E_{c_m}[q(c_m, c_r)]$ are nonincreasing functions, there is $q(c_m, c_r)$ that satisfies the incentive constraints, the participation constraints, and the balance condition.*

$$\begin{aligned}
\max_q \quad & E_{c_m c_r}\left\{\left[p(c_m, c_r) - c_r - c_m\right] q(c_m, c_r)\right\} \\
\text{s.t} \quad & E_{c_m c_r}\left\{\left[p(c_m, c_r) - c_r - c_m - \frac{F_1(c_m)}{f_1(c_m)} - \frac{F_2(c_r)}{f_2(c_r)}\right] q(c_m, c_r)\right\} \geq 0
\end{aligned} \quad (14)$$

The following conclusions were obtained to solve the above planning problem.

Proposition 5. *When c_m, c_r satisfies condition (15), there is an optimal solution $q^*(c_m, c_r)$, described as (16), to satisfy the*

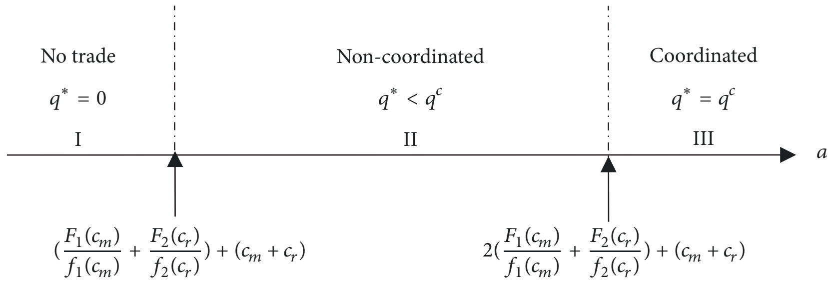

Figure 3: Supply chain coordination conditions.

incentive constraints, the participation constraints, and the balance condition.

$$2\left(\frac{F_1(c_m)}{f_1(c_m)} + \frac{F_2(c_r)}{f_2(c_r)}\right) \leq a - c_m - c_r \quad (15)$$

$$q^*(c_m, c_r) = \frac{a - c_m - c_r}{2b} = q^c(c_m, c_r) \quad (16)$$

At this time, the optimal trading amount is equal to the volume of the centralized decision with complete information, so the supply chain is coordinated.

Proposition 6. *When c_m, c_r satisfies condition (17), there is an optimal solution $q^*(c_m, c_r)$, described as (18), to satisfy the incentive constraints, the participation constraints, and the balance condition.*

$$\frac{F_1(c_m)}{f_1(c_m)} + \frac{F_2(c_r)}{f_2(c_r)} < a - c_m - c_r < 2\left(\frac{F_1(c_m)}{f_1(c_m)} + \frac{F_2(c_r)}{f_2(c_r)}\right) \quad (17)$$

$$q^*(c_m, c_r) = \frac{a - c_m - c_r}{2b} - \frac{1}{2b}\left[2\left(\frac{F_1(c_m)}{f_1(c_m)} + \frac{F_2(c_r)}{f_2(c_r)}\right) - (a - c_m - c_r)\right] \quad (18)$$

At this time, the optimal trading volume is less than the trading volume for a centralized decision with complete information. Because of the bilateral asymmetric information, the supply chain is not yet coordinated.

Proposition 7. *If the parameters do not satisfy formulas (15) and (17), then there is no solution to the programming problem in Lemma 4; that is, there is no order quantity that satisfies the incentive constraints, participation constraints, and the budget balance constraint.*

From the above conclusions, the parameter range can be divided into three regions that are complementary and disjointed (I, II, and III in Figure 3,), and there is an optimal solution in each region.

Market parameter a, the costs of both parties, and the risk rate $F_1(c_m)/f_1(c_m)$, $F_2(c_r)/f_2(c_r)$ determine the region divisions. In region I, market parameter a is relatively small; that is, the market environment is poor. The costs and risk rate on both sides are relatively large, or at least the costs of one party are larger, so that an inequality $a < (F_1(c_m)/f_1(c_m) + F_2(c_r)/f_2(c_r)) + (c_m + c_r)$ is present. Under such circumstances, the market is too small, the supply chain cost too high, and the supply chain revenue insufficient to compensate for the cost and information rent on the two sides; therefore, no transaction takes place between the two sides. However, in region III, the market parameter is large enough and the market environment is good, and the rents that distort the trading volume are less than the resulting supply chain returns; therefore, the supply chain does not reduce the rent by distorting the trading volume even if it needs to compensate for high information rents to motivate both parties to report their respective costs. As a result, the trading volume is the same as for the coordination. In particular, if the costs on both sides take the lower bound, then formula (15) is rewritten as $c_{m1} + c_{r1} \leq a$; that is, for a low cost enterprise, the supply chain must be coordinated, which is consistent with the unilateral reverse selection model (Jean-Jacques Laffont, David Martimort. The theory of incentive (Volume 1): the principal-agent model [M], Princeton University Press, 2002.).

In region II, the supply chain is not coordinated. The asymmetric information results in high information rent; therefore, to reduce the rent, the order quantity is distorted. Let $\Delta = q^c(c_m, c_r) - q^*(c_m, c_r)$ represent the order quantity distortion, that is, the difference between $q^c(c_m, c_r)$, the order quantity for full information and a centralized decision, and $q^*(c_m, c_r)$, the optimal order quantity for the incentive compatibility constraint, the participation constraint, and the balance condition under bilateral asymmetric information. From (18) we have

$$\Delta = \frac{1}{2b}\left[2\left(\frac{F_1(c_m)}{f_1(c_m)} + \frac{F_2(c_r)}{f_2(c_r)}\right) - (a - c_m - c_r)\right] > 0 \quad (19)$$

for which the following proposition is given.

Proposition 8. *When the order quantity is distorted, it is warped downward, and the higher the cost, the more serious the distortion.*

In fact, from the monotonic risk rate and formula (19), the first-order condition means

$$\Delta'_{c_m} = \frac{1}{2b}\left[2\left(\frac{F_1(c_m)}{f_1(c_m)}\right)'_{c_m} + 1\right] > 0 \tag{20}$$

$$\Delta'_{c_r} = \frac{1}{2b}\left[2\left(\frac{F_2(c_r)}{f_2(c_r)}\right)'_{c_r} + 1\right] > 0 \tag{21}$$

This illustrates the tradeoff between information rent and efficiency under bilateral asymmetric information. While the order quantity distortion reduces supply chain efficiency, it also reduces the information rents on both sides. Given other conditions, the higher the cost, the lower the unit product profit and the less profit lost due to trading volume distortions, making the distortion more serious.

Proposition 9. *The greater the price sensitivity of* $1/b$*, the greater the order quantity distortion.*

The greater the price sensitivity, the stronger the motivation to lie about the cost, and the more information the rent needed to prevent false report costs, the greater the order quantity distortion.

Proposition 10. *The larger the market parameter* a*, the smaller the order quantity distortion.*

If the market is good enough, as in area III in Figure 3, then the order quantity is not distorted, and the supply chain is coordinated.

4.2.3. Profit Allocation. Because $q^*(c_m, c_r)$ meets the incentive compatibility constraints of the program, both parties report their true costs; that is, $\widehat{c}_m = c_m$, $\widehat{c}_r = c_r$. Therefore, the contract is executed in the final stage according to the cost type $\widehat{c}_m, \widehat{c}_r$ as reported by both parties. The total supply chain profit is

$$\Pi^* = \left(p(\widehat{c}_m, \widehat{c}_r) - \widehat{c}_m - \widehat{c}_r\right) q^*(\widehat{c}_m, \widehat{c}_r) \tag{22}$$

From Lemma 3, the manufacturer and retailer rents are as follows:

$$\Pi_m(c_m) = \Pi_m^0 + \int_{c_m}^{c_{m2}} q^*(\widetilde{c}_m, \widehat{c}_r)\, d\widetilde{c}_m \tag{23}$$

$$\Pi_r(c_r) = \Pi_r^0 + \int_{c_r}^{c_{r2}} q^*(\widehat{c}_m, \widetilde{c}_r)\, d\widetilde{c}_r \tag{24}$$

The contract parameters are designed based on expected value; however, the contract is executed based on the actual reporting costs. Therefore, in the actual implementation, the total supply chain profit may be inconsistent with each party's rent sum; the difference between the two is $\Delta\Pi$, which is called the supply chain surplus and is described as

$$\Delta\Pi = \Pi^* - \left(\Pi_m(c_m) + \Pi_r(c_r)\right) \tag{25}$$

If $\Delta\Pi = 0$, then both parties' rents are equal to the total supply chain profit. If $\Delta\Pi < 0$, then the sum of their rents is more than the supply chain profit. If $\Delta\Pi > 0$, then the sum of their rents is less than the supply chain profit. Therefore, the profit allocation of both sides needs to be further adjusted so that both sides' profits are equal to the total supply chain profits, and each party's profits should be no less than the retained profits.

The following consideration is given to the allocation problem for $\Delta\Pi \neq 0$. The allocation ratio for the manufacturers and retailer is λ and $1-\lambda$, in which $0 \le \lambda \le 1$. For the manufacturer, we have

$$\Pi_m^*(c_m) = \Pi_m^0 + \int_{c_m}^{c_{m2}} q^*(\widetilde{c}_m, \widehat{c}_r)\, d\widetilde{c}_m + \lambda\Delta\Pi \tag{26}$$

If $\Delta\Pi > 0$, λ satisfies

$$\lambda \ge \max\left\{0, \frac{\int_{c_m}^{c_{m2}} q^*(\widetilde{c}_m, \widehat{c}_r)\, d\widetilde{c}_m}{-\Delta\Pi}\right\} \tag{27}$$

If $\Delta\Pi < 0$, λ satisfies

$$\lambda \le \min\left\{\frac{\int_{c_m}^{c_{m2}} q^*(\widetilde{c}_m, \widehat{c}_r)\, d\widetilde{c}_m}{-\Delta\Pi}, 1\right\} \tag{28}$$

For the retailer, we get

$$\Pi_r^*(c_r) = \Pi_r^0 + \int_{c_r}^{c_{r2}} q^*(\widehat{c}_m, \widetilde{c}_r)\, d\widetilde{c}_r + (1-\lambda)\Delta\Pi \tag{29}$$

If $\Delta\Pi > 0$, λ is given by

$$\lambda \le \min\left\{1 - \frac{\int_{c_r}^{c_{r2}} q^*(\widehat{c}_m, \widetilde{c}_r)\, d\widetilde{c}_r}{-\Delta\Pi}, 1\right\} \tag{30}$$

If $\Delta\Pi < 0$, λ is described as

$$\lambda \ge \max\left\{0, 1 - \frac{\int_{c_r}^{c_{r2}} q^*(\widehat{c}_m, \widetilde{c}_r)\, d\widetilde{c}_r}{-\Delta\Pi}\right\} \tag{31}$$

To sum up, we have the following propositions.

Proposition 11. *For* $\Delta\Pi > 0$*, if* λ *that satisfies the following conditions exists, the manufacturer and retailer reach a transaction and the contract is executed.*

$$\begin{aligned}\max\left\{0, \frac{\int_{c_m}^{c_{m2}} q^*(\widetilde{c}_m, \widehat{c}_r)\, d\widetilde{c}_m}{-\Delta\Pi}\right\} &\le \lambda \\ \le \min\left\{1 - \frac{\int_{c_r}^{c_{r2}} q^*(\widehat{c}_m, \widetilde{c}_r)\, d\widetilde{c}_r}{-\Delta\Pi}, 1\right\}&\end{aligned} \tag{32}$$

Proposition 12. *For* $\Delta\Pi < 0$*, if* λ *that satisfies the following conditions exists, the manufacturer and retailer reach a transaction, and the contract is executed.*

$$\begin{aligned}\max\left\{0, 1 - \frac{\int_{c_r}^{c_{r2}} q^*(\widehat{c}_m, \widetilde{c}_r)\, d\widetilde{c}_r}{-\Delta\Pi}\right\} &\le \lambda \\ \le \min\left\{\frac{\int_{c_m}^{c_{m2}} q^*(\widetilde{c}_m, \widehat{c}_r)\, d\widetilde{c}_m}{-\Delta\Pi}, 1\right\}&\end{aligned} \tag{33}$$

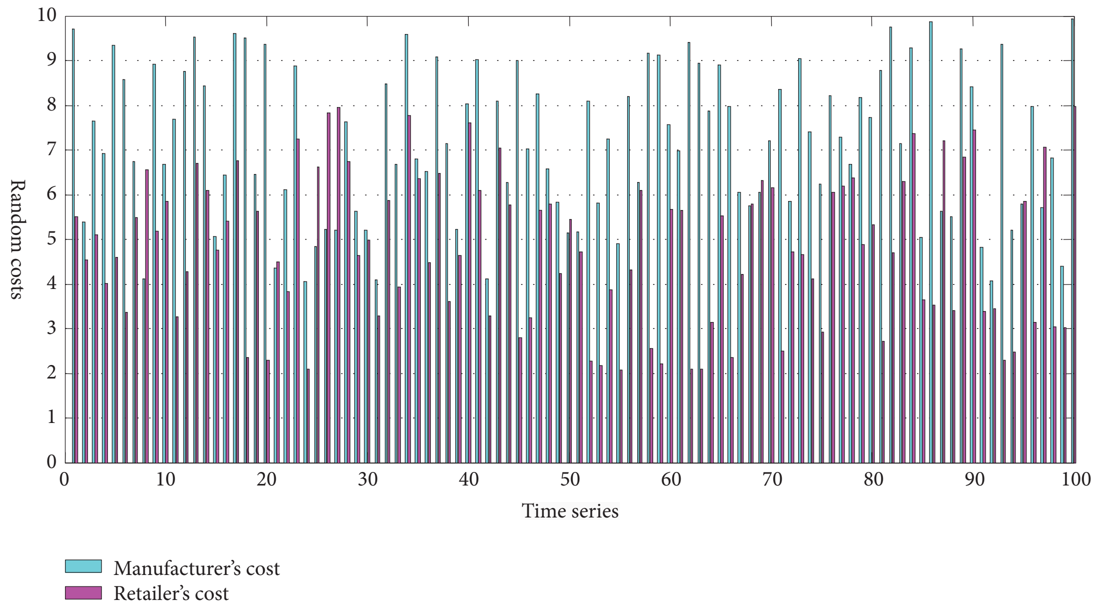

FIGURE 4: Random costs.

Therefore, the profits of the manufacturer and retailer are related to the reservation profit, the reporting cost, the order quantity, and λ, with the specific allocation ratio depending on the bargaining power of each party.

Propositions 11 and 12 give the conditions for whether a transaction can be reached. Here, we now determine how to define the optimal transfer payment when there is a transaction.

From the manufacturer's point of view,

$$\begin{aligned} t_1{}^*(\hat{c}_m,\hat{c}_r) &= \Pi_m^*(c_m) + \hat{c}_m q^*(\hat{c}_m,\hat{c}_r) \\ &= \Pi_m^0 + \int_{c_m}^{c_{m2}} q^*(\tilde{c}_m,\hat{c}_r)\, d\tilde{c}_m + \lambda\Delta\Pi \\ &\quad + \hat{c}_m q^*(\hat{c}_m,\hat{c}_r) \end{aligned} \tag{34}$$

From the retailer's point of view,

$$\begin{aligned} t_2{}^*(\hat{c}_m,\hat{c}_r) &= \left(p(\hat{c}_m,\hat{c}_r) - c_r\right) q^*(\hat{c}_m,\hat{c}_r) - \Pi_r^*(c_r) \\ &= \left(p(\hat{c}_m,\hat{c}_r) - c_r\right) q^*(\hat{c}_m,\hat{c}_r) \\ &\quad - \left\{\Pi_r^0 + \int_{c_r}^{c_{r2}} q^*(\hat{c}_m,\tilde{c}_r)\, d\tilde{c}_r + (1-\lambda)\Delta\Pi\right\} \end{aligned} \tag{35}$$

From the definition for $\Delta\Pi$, $t_1{}^*(\hat{c}_m,\hat{c}_r) = t_2{}^*(\hat{c}_m,\hat{c}_r)$ is obtained. Let $t^*(\hat{c}_m,\hat{c}_r) = t_i{}^*(\hat{c}_m,\hat{c}_r)$ for $i = 1, 2$.

4.2.4. Contract Execution. First, the manufacturer and the retailer acquire their own costs. Then, they report the costs according to the contract menu $\{q^*(c_m,c_r), t^*(c_m,c_r)\}$. Both sides report the costs truthfully because of the incentive function in the contract. Then, the trading volume is determined based on Propositions 5–7 and the reported costs. If $q^* = 0$, then the transaction is finished; otherwise, if λ of Propositions 11 or 12 does not exist, the transaction ends; if λ exists, the retailer's order quantity is q^*, and the manufacturer gets transfer payment t^*.

5. Numerical Simulations

The supply chain contract was simulated and then analyzed using specific parameters and distribution functions to ensure the conclusion and contract execution were more intuitive.

It was assumed that the respective costs were uniform distributions on $[4, 10]$ and $[2, 8]$, and the demand function was $p = a - bq$, where $a = 20$ and $b = 4$.

As was assumed, both sides had industry reservation profits $\Pi_m^0 = 1$ and $\Pi_r^0 = 0.5$ (Cost distribution function, mean value, variance, market parameters, and industry reservation profits will affect the decisions and profits of both sides, which can be adjusted according to the actual situation.). Random numbers for c_m and c_r were generated from the uniform distributions, as shown in Figure 4, 100 c_m and 100c_r, which were then put into 100 cost combinations $\{c_m, c_r\}$. In the later simulation, each cost combination was regarded as the cost of the upstream and downstream enterprises in the supply chain. That is, 100 supply chains were simulated to simulate order quantity, transfer payments, supply chain profit, and the profit for both sides.

Next, supply chain coordination, profit distribution, and contract execution were respectively analyzed, and the impacts of both parties' costs on the supply chain coordination and their profits discussed.

5.1. Coordination Analysis. Order quantity $q^*(c_m, c_r)$ and order quantity distortion were calculated using the decision conditions in Propositions 5–7 (Figure 5).

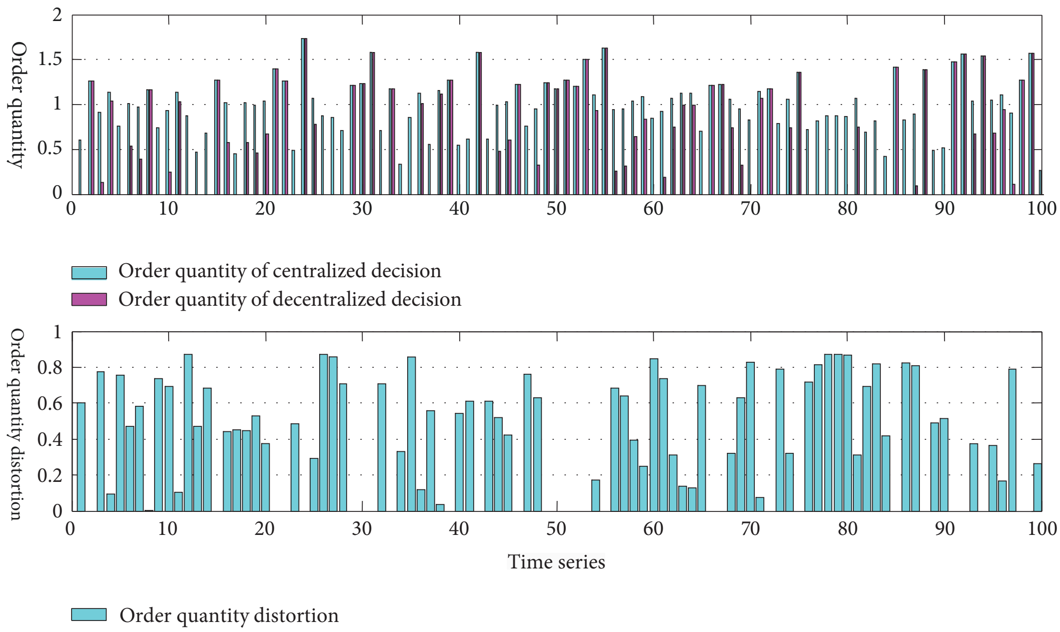

Figure 5: Order quantity and order quantity distortion.

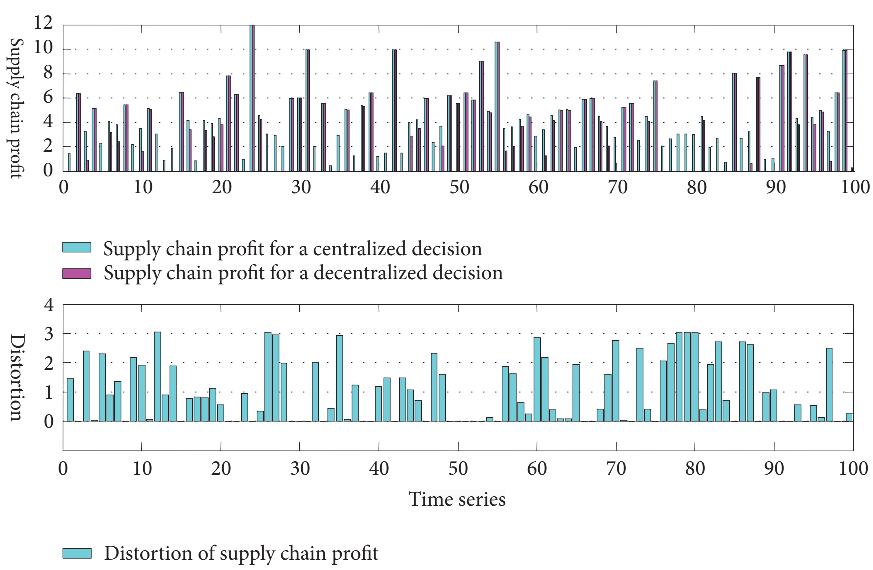

Figure 6: Supply chain profit and distortions.

As shown in Figure 3, when the parameters satisfied Proposition 5 (Area III in Figure 3), the supply chain was coordinated, in which $q^* = q^c$; therefore, there was no distortion (Figure 5). When the parameters satisfied Proposition 6 (Area II in Figure 3), the supply chain could not be coordinated; that is, $q^* < q^c$, and there was a downward distortion (Figure 5). When the parameters satisfied Proposition 7 (Area I in Figure 3), $q^* = 0$, indicating that there was no transaction. Therefore, the contract designed in this paper was shown to partially coordinate the supply chain.

From the order quantity and its associated distortion, the supply chain profit and its distortion (compared with the centralized decision) were correspondingly determined, as shown in Figure 6.

5.2. Supply Chain Profit Allocation. From Propositions 11 and 12, the profit allocation ratio interval was determined (Figure 7(a)), the specific value of which also depended on the position and bargaining power of each side in the supply chain. In the simulation, the mean of the interval was used to determine the allocation proportion, as shown in Figure 7(b).

In Figure 7, for some allocation proportions, the lower bound was higher than the upper bound or was greater than 1. For example, in combinations 87 and 97, the lower bound was

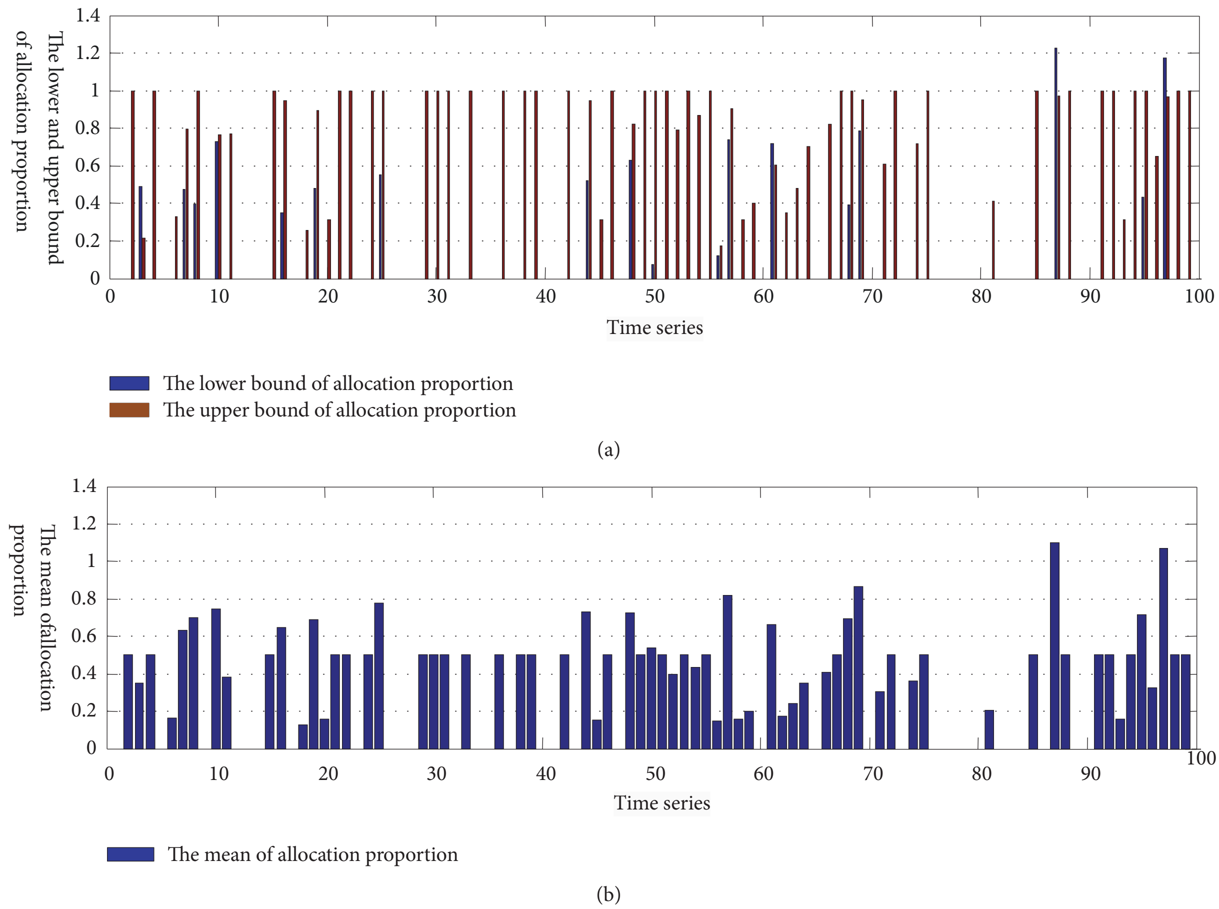

Figure 7: Allocation proportion.

greater than 1, indicating that the distribution proportions for Propositions 11 and 12 did not exist, and there could not be a transaction; therefore, combinations 87 and 97 were excluded.

For combinations 87 and 97, the profits before the manufacturer allocated the supply chain surplus (-3.3887 and -3.1142) were less than the reservation profits (reservation profits are 1), which meant that the manufacturers needed to share the supply chain surplus (3.5858 and 3.5053) to meet the reservation profit. The supply chain surplus needed by manufacturers was 1-(-3.3887) and 1-(-3.1142), which were more than the actual supply chain surplus 3.5858 and 3.5053; therefore, the lower bound of the allocation proportions was greater than 1.

In addition, from formulas (26) and (29), the profit for both sides was determined, as shown in Figure 8.

5.3. Contract Execution. From the definition for transfer payment t^*, we derived Figure 9.

The contract execution was as follows. The manufacturer and retailer know their own costs $\{c_m, c_r\}$ and then truthfully report their costs. Then, the optimal transaction volume $q^*(c_m, c_r)$ was determined using Figure 5, after which the corresponding transfer payment $t^*(c_m, c_r)$ was determined using Figure 9. The manufacturer then produced product $q^*(c_m, c_r)$ for the retailer, and the retailer paid $t^*(c_m, c_r)$ to the manufacturer. The transaction ends.

5.4. Static Analysis. In this subsection, the relationships between the profit and the costs of the two parties are analyzed, with the mean value in Section 5.2 being used as the allocation proportion. To better describe the relationship between profit and costs, it was assumed that one party's costs were fixed and the relationship between profit and the other's costs was explored.

Here, it was assumed that the retailer's costs were fixed at 3. The supply chain profit under centralized decision-making and asymmetric information, the manufacturer profits, and the retailer's profit were then simulated. As shown in Figure 10, different costs and different allocation rules result in different results; however, the basic conclusions are consistent.

From Figure 10, it can be seen that the relationship between profit and the manufacturer's cost roughly divided into three regions: I, II, III, which corresponded to the three regions in Figure 3; no transaction, noncoordination, and coordination. In a centralized decision-making environment, the supply chain profit monotonically decreases in all regions on the manufacturer's cost. Under asymmetric information, the supply chain profits in regions III and II decreased

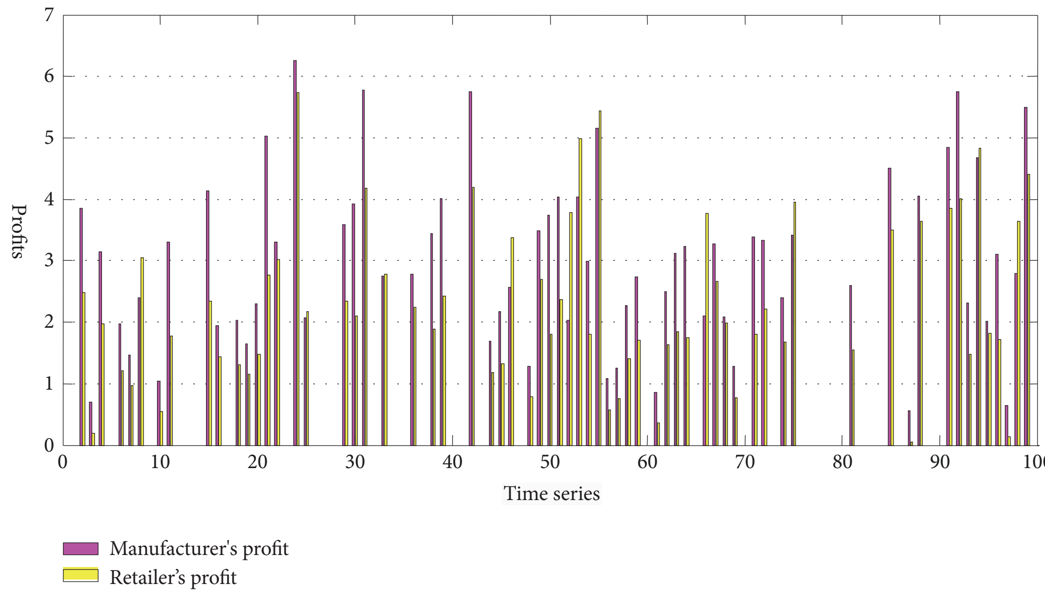

Figure 8: Profits of manufacturer and retailer.

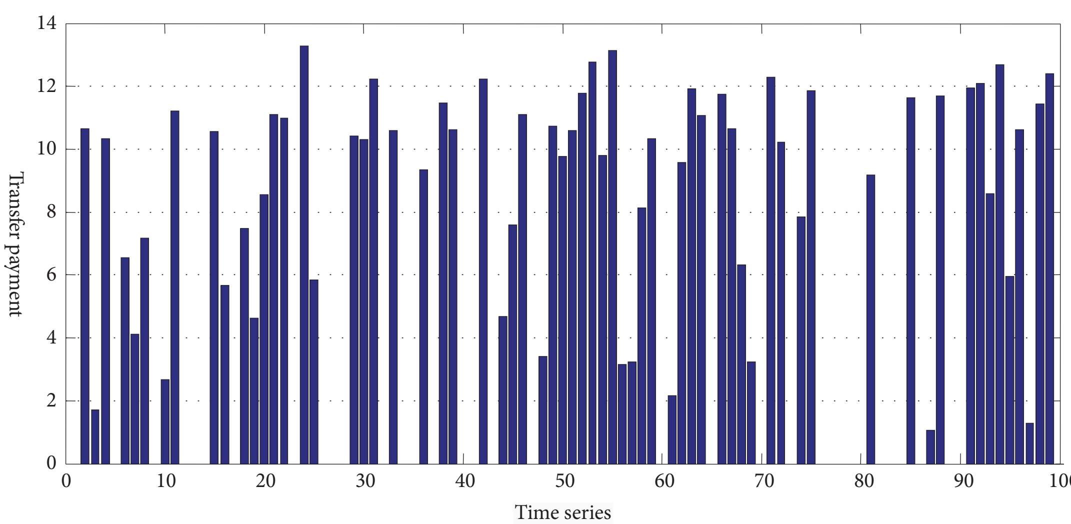

Figure 9: Transfer payment.

monotonically with an increase in manufacturer's cost, and there was no profit in region I. Under asymmetric information, the manufacturer's profit in regions III and II decreased monotonically with an increase in the manufacturer's costs, and there was no profit in region I. Under asymmetric information, the retailer's profit was similar.

The profit for the manufacturer and the retailer intersected in region III, and the manufacturer costs were greater than the retailer's cost as it was assumed that that the manufacturer's reservation profit was greater than the retailer's reservation profit. If this assumption is changed, the intersection location changes accordingly. If the retailer has large fixed costs, the intersection of the profits moves backwards; therefore, there would be no intersection in region III.

There is also a discontinuity in the manufacturer and the retailer profits between region III and the region II, at which point, there was an increase in the manufacturer's profit and a reduction in the retailer's profit (if the manufacturer's costs are fixed, the retailer's profit at the discontinuity increases, while the manufacturer's profit decreases) because of the different expressions for the order quantities in the two regions.

6. Conclusions

This paper focused on a single product supply chain consisting of a manufacturer and a retailer to determine the supply chain coordination conditions and the allocation of

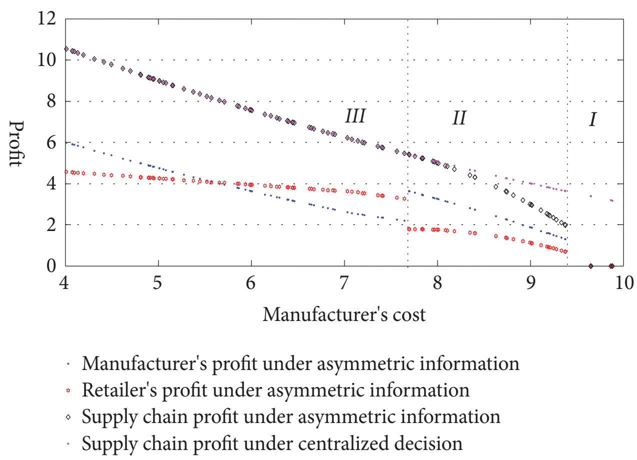

FIGURE 10: The relationship between profit and manufacturer's cost (for $c_r = 3$).

the supply chain surplus when a manufacturer and retailer have private cost information. Because the manufacturer and retailer have private information and the status of their core enterprises in the supply chain is difficult to determine, a bilateral adverse selection model was developed that introduced a virtual altruistic principal as the coordinating subject, from which the following conclusions were drawn.

First, three supply chain coordination regions were identified, with the region divisions depending on costs, private information structures, and market demand parameters. Second, when the order quantity was distorted, the degree of distortion was positively related to the costs of the two parties and price sensitivity and was negatively related to the market environment parameters. Third, the upper and lower bounds of the allocation proportion for the supply chain surplus were given. Finally, under the assumption that the costs of both parties obey a uniform distribution, a numerical simulation example was given, the contract execution simulated, and the relationship between the costs and profit analyzed.

In this paper, the supply chain coordination conditions were obtained even though the supply chain was not fully coordinated; however, the results were enlightening for supply chain management. In particular, for a supply chain in which the costs for each party are not fully disclosed, the supply chain can be partially coordinated. This paper proposed a contract mechanism under a simple two-level supply chain; however, the assumptions need to be further relaxed and the competitive supply chain coordination further studied. In addition, further consideration should be given to the supply chain coordination mechanism under other demand conditions. A subsequent study will continue to explore contract design to improve supply chain efficiency.

Appendix

Proof of Lemma 1. In fact, using the incentive compatibility constraint, for $\forall c_m, \widehat{c}_m \in [c_{m1}, c_{m2}]$, we have the following (Jean-Jacques Laffont, David Martimort. The theory of incentive (Volume 1): the principal-agent model [M], Princeton University Press, 2002.):

$$\begin{aligned} &E_{c_r}\left[t_1(c_m, c_r) - c_m q(c_m, c_r)\right] \\ &\quad \geq E_{c_r}\left[t_1(\widehat{c}_m, c_r) - c_m q(\widehat{c}_m, c_r)\right] \end{aligned} \tag{A.1}$$

$$\begin{aligned} &E_{c_r}\left[t_1(\widehat{c}_m, c_r) - \widehat{c}_m q(\widehat{c}_m, c_r)\right] \\ &\quad \geq E_{c_r}\left[t_1(c_m, c_r) - \widehat{c}_m q(c_m, c_r)\right] \end{aligned} \tag{A.2}$$

That is, no matter how much the manufacturer's cost, c_m or $\widehat{c}_m$, a true report is better than a false report. Adding (A.1) and (A.2) we obtain

$$(\widehat{c}_m - c_m)\left\{E_{c_r}\left[q(c_m, c_r)\right] - E_{c_r}\left[q(\widehat{c}_m, c_r)\right]\right\} \geq 0 \tag{A.3}$$

The incentive compatibility alone requires that the schedule for $E_{c_r}[q(\cdot, c_r)]$ has to be nonincreasing. Similarly, $E_{c_m}[q(c_m, \cdot)]$ is a monotonous and nonincreasing function of c_r. □

Proof of Lemma 2. From (7) and (8) we have the following (Jean-Jacques Laffont, Jean Tirole. A theory of incentive in procurement and regulation [M], MIT Press, 1993.) (Jean-Jacques Laffont, David Martimort. The theory of incentive (Volume 1): the principal-agent model [M], Princeton University Press, 2002.)

$$\frac{d\Pi_m(c_m)}{dc_m} = -E_{c_r}\left[q(c_m, c_r)\right] < 0 \tag{A.4}$$

$$\frac{d\Pi_r(c_r)}{dc_r} = -E_{c_m}\left[q(c_m, c_r)\right] < 0 \tag{A.5}$$

Therefore, the participation constraints are equivalent to $\Pi_m(c_{m2}) \geq \Pi_m^0$ and $\Pi_r(c_{r2}) \geq \Pi_r^0$.

In addition, it should be clear that participation constraints (9) and (10) are all binding when $c_m = c_{m2}$ and $c_r = c_{r2}$ at the optimum, i.e., $\Pi_m(c_{m2}) = \Pi_m^0$, $\Pi_r(c_{r2}) = \Pi_r^0$. Indeed, if this were not so, the principal could reduce either $\Pi_m(c_{m2})$ or (and) $\Pi_m(c_m)$ by a small amount ε, still keeping all outputs the same. This would increase the principal's payoff leading to a contradiction. Hence, we must have $\Pi_m(c_{m2}) = \Pi_m^0$. Similarly, we can get $\Pi_r(c_{r2}) = \Pi_r^0$. □

Proof of Lemma 4. $E_{c_m}[\Pi_m(c_m)] = \int_{c_{m1}}^{c_{m2}} \Pi_m(c_m) f_1(c_m) dc_m$, which, by an integration by parts and (12), gives

$$\begin{aligned} E_{c_m}\left[\Pi_m(c_m)\right] &= \int_{c_{m1}}^{c_{m2}} \Pi_m(c_m)\, dF_1(c_m) \\ &= \Pi_m(c_{m2}) \\ &\quad + E_{c_m c_r}\left[\frac{F_1(c_m)}{f_1(c_m)} q(c_m, c_r)\right] \end{aligned} \tag{A.6}$$

Calculate the expected value on both sides of (4) with respect to c_m, and we have

$$\begin{aligned} E_{c_m}\left[\Pi_m(c_m)\right] = {} & E_{c_m c_r}\left[t_1(c_m, c_r)\right] \\ & - E_{c_m c_r}\left[c_m q(c_m, c_r)\right] \end{aligned} \tag{A.7}$$

From (A.6) and (A.7) we obtain

$$\begin{aligned} &E_{c_m c_r}\left[t_1\left(c_m, c_r\right)\right] \\ &\quad= E_{c_m c_r}\left[\left(c_m + \frac{F_1\left(c_m\right)}{f_1\left(c_m\right)}\right) q\left(c_m, c_r\right)\right] + \Pi_m\left(c_{m2}\right) \end{aligned} \tag{A.8}$$

Similarly, $E_{c_r}[\Pi_r(c_r)] = \int_{c_{r1}}^{c_{r2}} \Pi_r(c_r) f_2(c_r) dc_r$, which, by an integration by parts and (13), gives

$$\begin{aligned} E_{c_r}\left[\Pi_r\left(c_r\right)\right] &= \int_{c_{r1}}^{c_{r2}} \Pi_r\left(c_r\right) dF_2\left(c_r\right) \\ &= \Pi_r\left(c_{r2}\right) + E_{c_m c_r}\left[\frac{F_2\left(c_r\right)}{f_2\left(c_r\right)} q\left(c_m, c_r\right)\right] \end{aligned} \tag{A.9}$$

Calculate the expected value on both sides of (5) with respect to c_r, and we get

$$\begin{aligned} E_{c_r}\left[\Pi_r\left(c_r\right)\right] &= E_{c_m c_r}\left\{\left[p\left(c_m, c_r\right) - c_r\right] q\left(c_m, c_r\right)\right\} \\ &\quad - E_{c_m c_r}\left[t_2\left(c_m, c_r\right)\right] \end{aligned} \tag{A.10}$$

(A.9) and (A.10) give

$$\begin{aligned} &E_{c_m c_r}\left[t_2\left(c_m, c_r\right)\right] \\ &\quad= E_{c_m c_r}\left\{\left[p\left(c_m, c_r\right) - c_r - \frac{F_2\left(c_r\right)}{f_2\left(c_r\right)}\right] q\left(c_m, c_r\right)\right\} \\ &\qquad - \Pi_r\left(c_{r2}\right) \end{aligned} \tag{A.11}$$

The budget balance constraint means that $E_{c_m c_r}[t_1(c_m, c_r)] = E_{c_m c_r}[t_2(c_m, c_r)]$. Using (A.8) and (A.11), we obtain

$$\begin{aligned} \Pi_m\left(c_{m2}\right) + \Pi_r\left(c_{r2}\right) &= E_{c_m c_r}\left\{\left[p\left(c_m, c_r\right) - c_r - c_m\right.\right. \\ &\quad \left.\left. - \frac{F_1\left(c_m\right)}{f_1\left(c_m\right)} - \frac{F_2\left(c_r\right)}{f_2\left(c_r\right)}\right] q\left(c_m, c_r\right)\right\} \end{aligned} \tag{A.12}$$

Since the participation constraints are equivalent to $\Pi_m(c_{m2}) = \Pi_m^0 \geq 0$ and $\Pi_r(c_{r2}) = \Pi_r^0 \geq 0$, the necessary conditions for $q(c_m, c_r)$ to be implemented are the nonnegative on the right side of (A.12), namely,

$$\begin{aligned} &E_{c_m c_r}\left\{\left[p\left(c_m, c_r\right) - c_r - c_m - \frac{F_1\left(c_m\right)}{f_1\left(c_m\right)} - \frac{F_2\left(c_r\right)}{f_2\left(c_r\right)}\right]\right. \\ &\quad \left. \cdot q\left(c_m, c_r\right)\right\} \geq 0 \end{aligned} \tag{A.13}$$

Therefore, if $q(c_m, c_r)$ is the solution to the following problem,

$$\begin{aligned} \max_q \quad & E_{c_m c_r}\left\{\left[p\left(c_m, c_r\right) - c_r - c_m\right] q\left(c_m, c_r\right)\right\} \\ \text{s.t} \quad & \text{(A.13)} \end{aligned} \tag{A.14}$$

then as long as $E_{c_r}[q(c_m, c_r)]$ and $E_{c_m}[q(c_m, c_r)]$ are nonincreasing functions, there is $q(c_m, c_r)$ that satisfies the incentive constraints, participation constraints, and balance conditions (Drew Fudenberg, Jean Tirole, *Game theory*, Massachusetts institute of technology, 1991.) □

Proofs of Propositions 5–7. Let $\mu \geq 0$ represent the Lagrange multiplier for (14); then the Lagrange function for the programming problem is

$$\begin{aligned} \psi\left(q, \mu\right) &= E_{c_m c_r}\left\{\left[\left(p\left(c_m, c_r\right) - c_r - c_m\right)\right.\right. \\ &\quad \left. + \mu\left(p\left(c_m, c_r\right) - c_r - c_m - \frac{F_1\left(c_m\right)}{f_1\left(c_m\right)} - \frac{F_2\left(c_r\right)}{f_2\left(c_r\right)}\right)\right] \\ &\quad \left. \cdot q\left(c_m, c_r\right)\right\} \end{aligned} \tag{A.15}$$

From $p = a - bq$ and the first-order condition, the optimal transaction volume $q^*(c_m, c_r)$ is defined using the following formula:

$$\begin{aligned} q^*\left(c_m, c_r\right) &= \frac{a - c_m - c_r}{2b} \\ &\quad - \frac{1}{2b} \frac{\mu}{1 + \mu}\left(\frac{F_1\left(c_m\right)}{f_1\left(c_m\right)} + \frac{F_2\left(c_r\right)}{f_2\left(c_r\right)}\right) \end{aligned} \tag{A.16}$$

In addition,

$$\begin{aligned} \frac{\partial \psi\left(q, \mu\right)}{\partial \mu} &= a - bq\left(c_m, c_r\right) - c_r - c_m - \frac{F_1\left(c_m\right)}{f_1\left(c_m\right)} \\ &\quad - \frac{F_2\left(c_r\right)}{f_2\left(c_r\right)} \geq 0 \end{aligned} \tag{A.17}$$

$$\mu \geq 0 \tag{A.18}$$

in which (A.17) and (A.18) satisfy the complementary relaxation condition. Let us discuss the conditions which μ and $q^*(c_m, c_r)$ must satisfy.

If $\mu > 0$, the complementary relaxation condition means

$$a - bq\left(c_m, c_r\right) - c_r - c_m - \frac{F_1\left(c_m\right)}{f_1\left(c_m\right)} - \frac{F_2\left(c_r\right)}{f_2\left(c_r\right)} = 0 \tag{A.19}$$

so

$$\begin{aligned} &q^*\left(c_m, c_r\right) \\ &\quad = \frac{a - c_m - c_r}{2b} \\ &\qquad - \frac{1}{2b}\left[2\left(\frac{F_1\left(c_m\right)}{f_1\left(c_m\right)} + \frac{F_2\left(c_r\right)}{f_2\left(c_r\right)}\right) - \left(a - c_m - c_r\right)\right] \end{aligned} \tag{A.20}$$

(A.16) and (A.20) imply that

$$\frac{1}{1 + \mu} = \frac{a - c_m - c_r}{F_1\left(c_m\right)/f_1\left(c_m\right) + F_2\left(c_r\right)/f_2\left(c_r\right)} - 1 \tag{A.21}$$

For $\mu > 0$, so we have

$$0 < \frac{a - c_m - c_r}{F_1\left(c_m\right)/f_1\left(c_m\right) + F_2\left(c_r\right)/f_2\left(c_r\right)} - 1 < 1 \tag{A.22}$$

Namely,

$$2\left(\frac{F_1(c_m)}{f_1(c_m)}+\frac{F_2(c_r)}{f_2(c_r)}\right)>(a-c_m-c_r)>\frac{F_1(c_m)}{f_1(c_m)}+\frac{F_2(c_r)}{f_2(c_r)} \tag{A.23}$$

This situation is internally consistent if (A.23) holds. We can verify that $q^*(c_m,c_r)$ makes $E_{c_r}[q(c_m,c_r)]$ and $E_{c_m}[q(c_m,c_r)]$ nonincreasing. In fact, using (A.20) we have

$$E_{c_r}[q(c_m,c_r)]=\frac{1}{b}E_{c_r}\left[-c_r-\frac{F_2(c_r)}{f_2(c_r)}\right]+\frac{1}{b}\left(a-c_m-\frac{F_1(c_m)}{f_1(c_m)}\right) \tag{A.24}$$

If $F_i(c)/f_i(c)$ is satisfied with the monotone-hazard-rate condition $(F_i(c)/f_i(c))'_c > 0$ (Patrick Bolton, Mathias Dewatripont. Contract theory [M], MIT Press, 2005.), then $E_{c_r}[q(c_m,c_r)]$ is nonincreasing in c_m. Similarly we can get $E_{c_m}[q(c_m,c_r)]$, which is nonincreasing in c_r.

Therefore, there is $q^*(c_m,c_r)$ that satisfies the incentive constraints, participation constraints, and balance conditions when c_m, c_r are satisfied with (A.23). At this time, the optimal transaction volume is less than the volume of the centralized decision with complete information. Because of the existence of bilateral asymmetric information, the supply chain is not yet coordinated.

If $\mu=0$, we have

$$a-bq(c_m,c_r)-c_r-c_m-\frac{F_1(c_m)}{f_1(c_m)}-\frac{F_2(c_r)}{f_2(c_r)}\geq 0 \tag{A.25}$$

So

$$q^*(c_m,c_r)\leq\frac{a-c_m-c_r}{2b}-\frac{1}{2b}\left[2\left(\frac{F_1(c_m)}{f_1(c_m)}+\frac{F_2(c_r)}{f_2(c_r)}\right)-(a-c_m-c_r)\right] \tag{A.26}$$

And (A.16) means

$$q^*(c_m,c_r)=\frac{a-c_m-c_r}{2b}=q^c(c_m,c_r) \tag{A.27}$$

Thus

$$\frac{a-c_m-c_r}{2b}\leq\frac{a-c_m-c_r}{2b}-\frac{1}{2b}\left[2\left(\frac{F_1(c_m)}{f_1(c_m)}+\frac{F_2(c_r)}{f_2(c_r)}\right)-(a-c_m-c_r)\right] \tag{A.28}$$

Namely,

$$2\left(\frac{F_1(c_m)}{f_1(c_m)}+\frac{F_2(c_r)}{f_2(c_r)}\right)\leq a-c_m-c_r \tag{A.29}$$

This situation is internally consistent if (A.29) holds. We can verify that $q^*(c_m,c_r)$ makes $E_{c_r}[q(c_m,c_r)]$ and $E_{c_m}[q(c_m,c_r)]$ nonincreasing.

Therefore, there is $q^*(c_m,c_r)$ that satisfies the incentive constraints, participation constraints, and balance conditions when c_m, c_r are satisfied with (A.29). At this time, the optimal transaction volume is the same as the volume for the complete information centralized decision, and the supply chain is coordinated. □

Data Availability

In the data of Section 5, we use simulated data. Under the assumption that the cost of manufacturer and retailer is uniform distribution, 100 random number pairs are generated. On this basis, we use our model results to study the character of order quantity, transfer payment, supply chain profit, and so on. Cost data is generated randomly, but it will not affect the related character. Readers can try their own way.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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