Coordination of New Energy Vehicle Supply Chain Considering Quality Improvement under the Dual-Credit Policy

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Abstract. Aiming at the higher requirements on product quality imposed by the dual-credit policy, this study takes the two-level supply chain system composed of a single battery supplier and a single new energy vehicle manufacturer as the object of study. On the basis of comprehensively considering the impact of factors such as point price, quality effort level and consumer preference on supply chain profits, this study uses game theory methods to construct supply chain decision-making models of centralized decision-making, decentralized decision-making, and coordination contracts. And the coordinated effect of the cost-sharing contract and the revenue-sharing contract is investigated through numerical analysis. The study findings indicate that as the price of credits grows, both the cost-sharing and benefit-sharing ratios also increase. Additionally, the suppliers' degree of quality effort increases, but the selling price of NEV falls. The manufacturer implements the cost-sharing contract when the quality cost coefficient falls within a specific range. When the coefficient for the cost of quality is high, both coordination mechanisms can accomplish Pareto improvement. However, the gain-sharing contract is superior in terms of enhancing the supplier's product quality level and overall profitability of the supply chain.

Keywords: new energy vehicle supply chain; stackleberg game; supply chain coordination

1 INTRODUCTION

With the global carbon emission problem becoming increasingly prominent, new energy vehicles (NEVs) have emerged as a key driving force in the development of the automotive industry, offering a low-carbon and environmentally friendly mode of transport. In 2018, China implemented the Measures for the Parallel Management of Average Fuel Consumption and New Energy Vehicle Points for Passenger Vehicle Enterprises. This policy has spurred traditional car companies to expedite their move into the NEV sector and has simultaneously encouraged NEV companies to enhance the quality of their core products. Research by Liang et al. [1] and Zhu et al. [2] indicates that consumers prioritize the quality and safety of vehicles, highlighting the importance

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for automotive enterprises to focus on the research and development of vehicle technology and the enhancement of vehicle performance. Data from 2023 reveals a significant rise in quality complaints for NEVs, mainly attributed to the inadequate quality innovations and systems among upstream suppliers. Amidst intense competition, quality issues have emerged as a significant barrier to industry growth, with the product quality of upstream suppliers being critical to the overall integrity of NEVs [3]. In practice, suppliers often shoulder the entire burden of R&D costs, while manufacturers reap greater benefits from the quality innovations introduced by suppliers. This imbalance between costs and benefits can lead to a reduction in suppliers' motivation, thereby impacting the quality and efficiency of the entire supply chain [4]. Consequently, how to effectively incentivise component suppliers to improve product quality has become an urgent issue in the supply chain management of NEVs.

In order to address this issue, several scholars have conducted relevant research. Xiao et al. [5] analyzed the game equilibrium among supply chain members under various scenarios, including centralized decision-making in the supply chain, supplier cooperation, supplier non-cooperation, and mixed situations. They discovered that supplier cooperation can to a certain extent enhance the quality efforts of suppliers. Furthermore, the research by Liu et al. [6] highlighted that a revenue-sharing contract model can effectively elevate the product quality level of suppliers. In addition, Fan et al. [7] developed a supply chain coordination contract model under a wholesale price-quality cost-sharing agreement, confirming that it can also notably improve both the product quality and order quantity for suppliers. Building on previous studies, this paper will delve deeper into the coordination effects of cost-sharing and benefit-sharing contracts within the NEV supply chain and offer strategic recommendations for the healthy development of the NEV industry.

In summary, following the implementation of the dual-credit policy, points will emerge as a new tradable commercial resource, and the value of these points will significantly influence the production decisions and product quality of NEV manufacturers. Based on this, this paper provides more in-depth insights into vertical cooperation between new energy vehicle manufacturers and suppliers by analysing what contractual mechanisms manufacturers use to effectively incentivise upstream suppliers to improve their product quality. Ultimately, numerical analyses are conducted to examine the variations in suppliers' quality levels and the profits of supply chain members under different contractual arrangements.

2 PROBLEM DESCRIPTION AND ASSUMPTIONS

2.1 Description of the Problem

This study specifically examines a two-tier supply chain comprising of producers of new energy vehicles and core component suppliers. Given the important role of battery quality in the performance, safety, and cost components of new energy vehicles, this paper focuses on core component suppliers as battery suppliers. Driven by the policy and consumer demand for high-quality products, the manufacturer provides a benefit-sharing contract and a cost-sharing contract to the battery supplier, and the battery supplier makes quality improvement decisions based on the provided contract.

2.2 Research hypothesis

Assumption 1: Let the manufacturer and the battery supplier both produce and sell a product in a single cycle. The battery supplier's cost of manufacturing the product is d and the wholesale price is w .

Assumption 2: According to the policy, NEV can earn points if they meet the quality standards of range, energy density and power consumption, among which the battery quality is the core that affects the range. Therefore, let k be the product quality effort level of the battery supplier, the trading price of points is e , so the point income of each new energy vehicle is eHk , and H is the point accounting coefficient.

Assumption 3: According to Aspremont et al. [8] this paper takes the cost spent by the battery supplier in making quality improvement as $c(k) = nk^2 / 2$, n is the investment coefficient of quality cost of the battery supplier.

Assumption 4: According to Yu et al. [9] the market demand function for NEV shows a linear relationship in terms of price and quality effort level, i.e. $D = a - bp + \lambda k$, where a represents the potential size of the new energy vehicle market; b is the sensitivity coefficient of the price of the new energy vehicle; p is the selling price of the new energy vehicle; and λ is the sensitivity coefficient of the consumer's concern about product quality.

For the convenience of discussion, the superscripts "0, 1, 2, 3" are used to represent decentralised decision-making, centralised decision-making, cost-sharing contract, and benefit-sharing contract, respectively. Π_{sc} represents the overall profit of the supply chain, and Π_s and Π_r represent the profit functions of the supplier and the manufacturer, respectively.

3 MODEL CONSTRUCTION

3.1 Decentralised Decision-Making

Under decentralised decision-making, the battery supplier is the dominant player and the manufacturer is the follower, making decisions with the goal of maximising their respective profits, so the supply chain of NEV carries out the Stackleberg game, and the order of the game is as follows: first of all, the battery supplier determines the level of product quality and the wholesale price, and then, the manufacturer makes decisions on the selling price of the whole vehicle, and adopts the inverse induction method to solve the above problems. At this time, the battery supplier and the new energy vehicle manufacturer's respective benefit function is:

$$\Pi_s^0 = (w - d)(a - bp + \lambda k) - nk^2 / 2 \tag{1}$$

$$\Pi_r^0 = (p - w + eHk)(a - bp + \lambda k) \tag{2}$$

Make the first order partial derivatives of p in equation (2) to be 0 to get $p^0 = a + b(w - eHk) + k\lambda / 2b$, and substitute it into the supplier to get the first order partial derivatives of the parallel standing w and k in the profit function to be equal to 0 to get:

$$\Pi_s^{0\prime} = [(d - w)(a + beHk - bw + k\lambda) - nk^2]/2 \tag{3}$$

$$\begin{cases} w^{0*} = d - 2(a - bd)n / b^2e^2H^2 - 4bn + 2beH\lambda + \lambda^2 \\ k^{0*} = -(a - bd)(beH + \lambda) / b^2e^2H^2 - 4bn + 2beH\lambda + \lambda^2 \end{cases} \tag{4}$$

The Hessian matrix of decision variables w and k in formula (3) is as follows:

$$H_1 = \begin{bmatrix} \dfrac{\partial^2 \Pi_s^{0\prime}}{\partial w^2} & \dfrac{\partial^2 \Pi_s^{0\prime}}{\partial w \partial k} \\ \dfrac{\partial^2 \Pi_s^{0\prime}}{\partial k \partial w} & \dfrac{\partial^2 \Pi_s^{0\prime}}{\partial k^2} \end{bmatrix} = \begin{bmatrix} -b & \dfrac{1}{2}(beH + \lambda) \\ \dfrac{1}{2}(beH + \lambda) & -n \end{bmatrix}$$

When satisfying $-b < 0$ and $1/4(-b^2e^2H^2 + 4bn - 2beH\lambda - \lambda^2) > 0$, H_1 is referred to as a negative definite matrix , so w^{0*} and k^{0*} are the unique optimal solutions. Substituting them into p, we obtain:

$$p^{0*} = aeH(beH + \lambda) + d(-bn + beH\lambda + \lambda^2) - 3an / [4bn - (\lambda + beH)^2] \tag{5}$$

The optimal solution obtained is obtained by substituting into the profit function of the manufacturer and supplier:

$$\Pi_s^{0*} = (bd - a)^2 n / 2(b^2e^2H^2 - 4bn + 2beH\lambda + \lambda^2) \tag{6}$$

$$\Pi_r^{0*} = bn^2 (a - bd)^2 / (b^2e^2H^2 - 4bn + 2beH\lambda + \lambda^2)^2 \tag{7}$$

$$\Pi_{sc}^{0*} = \frac{(a - bd)^2 n (b^2e^2H^2 - 6bn + 2beH\lambda + \lambda^2)}{2(4bn - b^2e^2H^2 - 2beH\lambda - \lambda^2)^2} \tag{8}$$

3.2 Centralised Decision-Making

In the centralised model, the NEV supply chain generates the following aggregate profit:

$$\Pi_{sc}^1 = (p - d + eHk)(a - bp + \lambda k) - nk^2 / 2 \tag{9}$$

By simultaneously setting the first-order partial derivatives of p and k in Equation (9) to zero and substituting them into the profit function, we obtain:

$$\begin{cases} k^{1*} = (a-bd)(beH+\lambda)/2bn-(\lambda-beH)^2 \\ p^{1*} = \dfrac{-an+aeH(beH+\lambda)+d(-bn+beH\lambda+\lambda^2)}{b^2e^2H^2-2bn+2beH\lambda+\lambda^2} \end{cases} \tag{10}$$

$$\Pi_{sc}^{1*} = (a-bd)^2 n/2[2bn-(\lambda+beH)^2] \tag{11}$$

Theorem 1 Compared to centralised decision making, the level of quality effort of suppliers, overall profitability of the supply chain, and the price at which the product is sold are lower and higher under decentralised decision making: $k^{0*} > k^{1*}$, $\Pi_{sc}^{0*} > \Pi_{sc}^{1*}$, $p^{0*} < p^{1*}$.

Proof: An analysis of variance between centralised and decentralised decision-making yields $k^{0*}-k^{1*} = \dfrac{2b(a-bd)n(beH+\lambda)}{[be^2H^2-(2+\lambda+beH)]^2}$; $k^{0*}-k^{1*}>0$ $p^{0*}-p^{1*} = -\dfrac{2(a-bd)n(bn-beH\lambda-\lambda^2)}{[be^2H^2-(2+\lambda+beH)]^2}$ $p^{0*} < p^{1*}$ $\Pi_{sc}^{0*}-\Pi_{sc}^{1*} = \dfrac{2b^2(a-bd)^2n^3}{(b^2e^2H^2-4bn+2beH\lambda+\lambda^2)^2(2bn-b^2e^2H^2-2beH\lambda-\lambda^2)}$; $\Pi_{sc}^{0*}-\Pi_{sc}^{1*}>0$

Theorem 1 shows that in a centralised decision-making model consumers can buy better quality products at lower prices, and the supply chain is more profitable, illustrating the double marginal effect that exists in a decentralised decision-making model. In a decentralised model, suppliers are often somewhat limited in their motivation due to their own revenue and cost considerations, resulting in a lower level of effort in product quality improvement.

4 COORDINATION MECHANISMS

4.1 Cost-sharing Compacts

The cost of the supplier's quality effort is shared by the manufacturer in proportion ρ , given that the profit functions of the supplier and the manufacturer are as follows:

$$\Pi_s^2 = (w-d)(a-bp+\lambda k)-(1-\rho)nk^2/2 \tag{12}$$

$$\Pi_r^2 = (p-w+eHk)(a-bp+\lambda k)-\rho nk^2/2 \tag{13}$$

As above, by using backward induction for solving, setting the first-order partial derivative of p in formula (13) to 0 yields $p = a+b(w-eHk)+k\lambda/2b$.

After substituting p into equation (12), and simultaneously setting the first-order partial derivatives with respect to w and k to 0, we obtain:

$$\begin{cases} w^{2*} = 2n(1-\rho)(a-bd) - d(\lambda + beH)^2 / 4bn(1-\rho) - (\lambda + beH)^2 \\ k^{2*} = (a-bd)(beH+\lambda) / 4bn(1-\rho) - (\lambda + beH)^2 \end{cases} \tag{14}$$

Substituting the previously obtained values of w^{2*} and k^{2*} into p, we get:

$$p^{2*} = \frac{a\left(eH\left(beH+\lambda\right)+3n\left(-1+\rho\right)\right)+d\left(beH\lambda+\lambda^2+bn\left(-1+\rho\right)\right)}{(\lambda+beH)^2+4bn\left(\rho-1\right)} \tag{15}$$

Substituting the obtained optimal variables into equations (12) and (13), we get:

$$\Pi_s^{2*} = \left(a-bd\right)^2 n\left(-1+\rho\right) / 2\left(b^2e^2H^2 + 2beH\lambda + \lambda^2 + 4bn\left(-1+\rho\right)\right) \tag{16}$$

$$\Pi_r^{2*} = \frac{-\left(a-bd\right)^2 n\left(b^2e^2H^2\rho + \lambda^2\rho - 2b\left(n\left(-1+\rho\right)^2 - eH\lambda\rho\right)\right)}{2\left(b^2e^2H^2 + 2beH\lambda + \lambda^2 + 4bn\left(-1+\rho\right)\right)^2} \tag{17}$$

Theorem 2 The optimal cost sharing ratio is $\rho = \left(beH+\lambda\right)^2 / 8bn$ when $n \geq 3\left(beH+\lambda\right)^2 / 8b$.

Theorem 2 This leads to a range of quality cost coefficients for the manufacturer to offer cost sharing contracts to the suppliers, when the quality cost coefficients $n \geq 3\left(beH+\lambda\right)^2 / 8bn$, the car manufacturer will make optimal profit and hence will offer cost sharing contracts to the battery suppliers.

4.2 Revenue Sharing Contracts

When the manufacturer and supplier each receive ϕ percent of the revenue generated from the sale of NEVs, the supplier's and manufacturer's profit functions are as follows:

$$\Pi_s^3 = (w + \phi p - d)(a - bp + \lambda k) - nk^2 / 2 \tag{18}$$

$$\Pi_r^3 = [(1-\phi)\ p - w + eHk](a - bp + \lambda k) \tag{19}$$

Ibid:

$$\begin{cases} k^{3*} = (a-bd)(beH+\lambda)/2bn(2-\phi)-(\lambda+beH)^2 \\ w^{3*} = \dfrac{[b^2de^2H^2 - d\lambda^2(\phi-1) - a(2n(\phi-1)^2 + eH\lambda\phi)]}{2bn(2-\phi)-(\lambda+beH)^2} \\ + \dfrac{+b[-deH\lambda(\phi-2)+2dn(\phi-1)-ae^2H^2\phi]}{2bn(2-\phi)-(\lambda+beH)^2} \end{cases} \tag{20}$$

$$p^{3*} = \frac{aeH(beH+\lambda)+d(-bn+beH\lambda+\lambda^2)+an(2\phi-3)}{b^2e^2H^2+\lambda^2+2b[eH\lambda+n(\phi-2)]} \tag{21}$$

$$\Pi_s^{3*} = (a-bd)^2 n/2[2bn(2-\phi)-(\lambda+beH)^2] \tag{22}$$

$$\Pi_r^{3*} = b(a-bd)^2 n^2(-1+\phi)/2[2bn(2-\phi)-(\lambda+beH)^2 \tag{23}$$

Theorem 3 When $n \geq (beH+\lambda)^2/2bn$ the manufacturer provides the supplier with a revenue sharing ratio $\phi = (beH+\lambda)^2/(2bn)$.

From Theorem 3, the range of quality costs of the revenue sharing contract offered by the manufacturer to the supplier can be obtained, and the manufacturer obtains optimal profit when $n \geq (beH+\lambda)^2/2bn$ and therefore will offer a revenue sharing percentage.

5 ANALYSIS OF MODELS IN DIFFERENT SCENARIOS

By solving the models above, ρ^* and ϕ^* are substituted into the sales price, product quality effort level and profit functions of the cost-sharing contract model and the revenue-sharing contract model, respectively, for the following analyses.

Proposition 1 $\frac{\partial k^{0*}}{\partial e} > 0, \frac{\partial k^{1*}}{\partial e} > 0, \frac{\partial k^{2*}}{\partial e} > 0, \frac{\partial k^{3*}}{\partial e} > 0$; $\frac{\partial p^{0*}}{\partial e} < 0, \frac{\partial p^{1*}}{\partial e} < 0, \frac{\partial p^{2*}}{\partial e} < 0, \frac{\partial p^{3*}}{\partial e} < 0$

Proposition 1 posits that there exists a positive correlation between the points trading price and the level of quality effort exhibited by the supplier; whereas the selling price is lower, this is because the points trading increases the manufacturer's revenue stream and therefore the manufacturer is willing to reduce some of the price to increase sales.

Proposition 2 $\frac{\partial k^{0*}}{\partial \lambda} > 0, \frac{\partial k^{1*}}{\partial \lambda} > 0, \frac{\partial k^{2*}}{\partial \lambda} > 0, \frac{\partial k^{3*}}{\partial \lambda} > 0$; $\frac{\partial p^{0*}}{\partial \lambda} > 0, \frac{\partial p^{1*}}{\partial \lambda} > 0, \frac{\partial p^{2*}}{\partial \lambda} > 0, \frac{\partial p^{3*}}{\partial \lambda} > 0$

Proposition 2 suggests that when suppliers make quality technology investments, the higher the consumers' preference for quality levels and the higher the demand, the higher the benefits that suppliers derive from making product quality enhancements, and hence the suppliers choose to increase their quality effort levels. When consumer preference for quality increases, it indicates that consumers exhibit a willingness to pay a premium for enhancements in quality, and suppliers will accordingly increase their level of effort.

Proposition 3 When $(beH+\lambda)^2/4b \le n < 3(beH+\lambda)^2/8b$ is $\Pi_r^{2*}-\Pi_r^{0*}<0, \Pi_r^{3*}<0$, $\Pi_r^{2*}<0$ then the manufacturer does not offer any covenants; when $3(beH+\lambda)^2/8b \le n < (beH+\lambda)^2/2b$, $\Pi_r^{2*}-\Pi_r^{0*}>0, \Pi_r^{3*}<0$, the manufacturer offers cost-sharing covenants; and when $n \ge (beH+\lambda)^2/2b$, $\Pi_r^{3*}>\Pi_r^{2*}>\Pi_r^{0*}$, then the manufacturer preferentially offers revenue-sharing covenants.

Proposition 3 states that a manufacturer's choice of contract to a supplier is influenced by the cost coefficient of quality effort. When the cost of quality coefficient is low, the supplier develops on its own and the manufacturer does not need to provide a contract; when the cost of quality coefficient falls under a specific range, the manufacturer offers a cost-sharing contract; and when the cost is high, it provides a revenue-sharing contract. In addition, benefit-sharing contracts increase supplier quality effort and supply chain profitability more than cost-sharing contracts. Cost-sharing contracts reduce suppliers' marginal costs to improve quality, while revenue-sharing contracts allow suppliers to flexibly price and adjust quality to achieve higher returns.

Proposition 4 $\frac{\partial \rho^*}{\partial e}>0, \frac{\partial \phi^*}{\partial e}>0$.

Proposition 4 suggests that manufacturers are willing to offer higher cost-sharing ratios and benefit-sharing ratios as the trading price of points increases. From the expressions of ρ^* and ϕ^*, if $\lambda^* \to 0, e \to 0$, then $\rho^* \to 0, \phi^* \to 0$. Due to the policy, points trading has become a new profit growth point for manufacturers.

6 NUMERICAL ANALYSIS

To authenticate the accuracy of the aforementioned model, based on the example data from the literature [10] and the Measures for Calculating the Points of New Energy Passenger Vehicle Models, the necessary parameters in the model solution mentioned above must meet the following conditions: $a-bd>0,\ 2bn-(\lambda+beH)^2>0$, Matlab is used to draw the image for the analysis of the example.

6.1 Analysis of the impact of points trading prices

Take the parameter $a=200, b=15, d=4, \lambda=6, n=5, H=0.8, 0<e<0.52$. Figures 1 and 2 illustrate the impact that analyzing the price of points has on the quality effort and profit levels of supply chain participants in various decision situations.

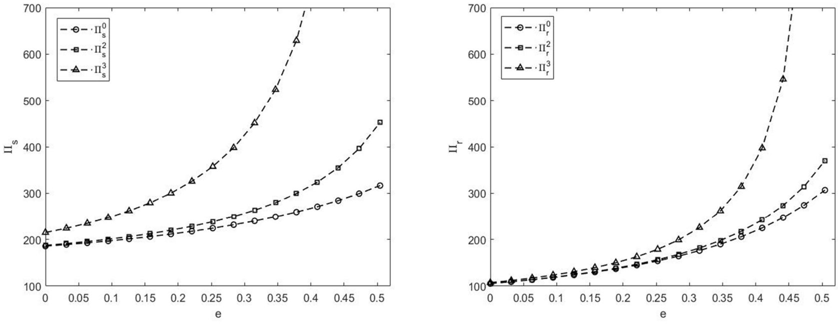

Fig. 1. Impact of credit prices on battery suppliers' and manufacturers' margins

According to Figure 1, when e meets $0 < \lambda + ebH < \sqrt{2bn}$, the revenue-sharing contract makes profits higher than other models, and the rise in the price of points results in a corresponding increase in the profits of manufacturers and suppliers, so it is evident that the policy significantly affects the profit development of NEV supply chain participants. The government should maintain the stability of the credits market and promote its healthy development; for manufacturers, they can increase profits by establishing revenue-sharing contracts with battery suppliers.

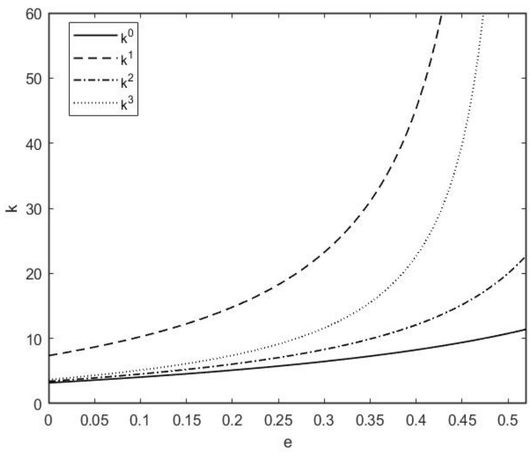

Fig. 2. Effect of points price on the level of quality effort in different models

According to Fig. 2, it can be seen that when $2bn-(\lambda+beH)^2>0$, The quality effort level under the revenue sharing contract exceeds that of the decentralized decision-making and cost-sharing contract, but remains lower than that of centralized decision making. Additionally, it grows as the price of credits increases, so the revenue sharing contract promotes mutually beneficial outcomes for all parties of the supply chain.

6.2 Quality Cost Factor Impact Analysis

Take the parameter $a = 200, b = 15, d = 4, \lambda = 6, e = 0.5, H = 0.8$. Figures 3 and 4 demonstrate the impact of the quality cost coefficient on profit and quality level of the members within the new energy vehicle supply chain.

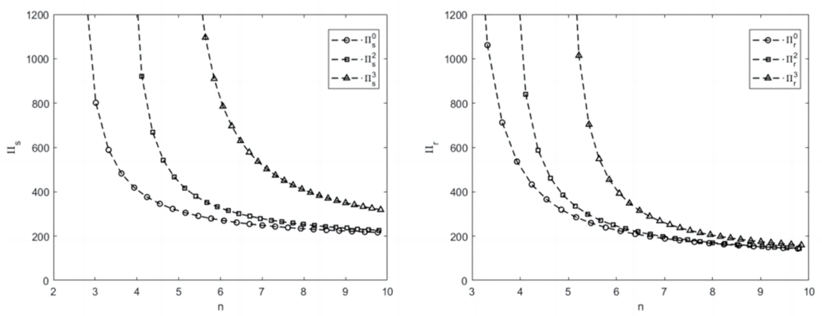

Fig. 3. Impact of quality cost coefficients on suppliers' and manufacturers' profits

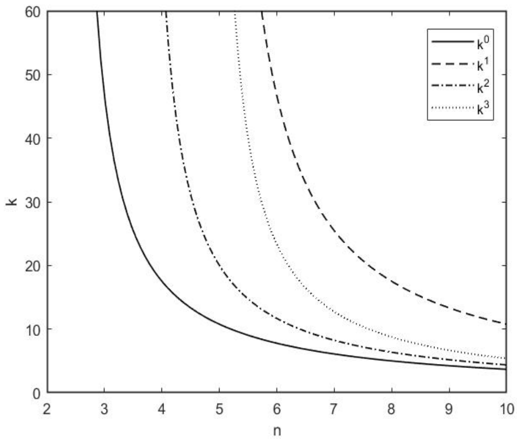

Fig. 4. Effect of quality cost coefficient on quality level

According to Figures 3 to 4, it is found that: when the price integral remains constant, the profit and quality level of both suppliers and manufacturers decline as the quality cost coefficient increases; when n is small, the manufacturer does not provide any contract to the suppliers, and the suppliers make their own decisions about the quality; as n increases, the manufacturer provides a cost sharing contract, at this time the supplier's quality endeavour level is gradually increased; and when $n \geq (\lambda + beH)^2 / 2b$, manufacturers provide revenue sharing contracts to optimize supplier quality efforts. It can be seen that when there is no significant technological advantage or when faced with high quality cost coefficients, revenue-sharing contracts can effectively mitigate the adverse effects.

7 CONCLUSION

This study analyzes the decision-making behaviors of NEV supply chain members aimed at improving product quality through vertical cooperation, set against the backdrop of the dual-credit policy. It also explores the combined effects of the policy and cooperation contracts on the supply chain's quality enhancement decisions. The findings of the study are as follows: 1) The policy is conducive to collaborative research and development in the NEV supply chain, the policy's requirement on product quality increases the importance of quality for supply chain members, and the points trading mechanism provides a new source of profit for manufacturers. Therefore, while improving the quality level, the selling price of automobiles also decreases; 2) In the price of points, in order to obtain more revenue, prompting the manufacturer to increase the proportion of cost-sharing and revenue-sharing ratio of the suppliers, and strengthen the supply chain co-operation. 3)choice of contract mode is related to the quality cost coefficient, when the quality cost is low, the manufacturer does not offer any contract, when the quality cost is high, both contract modes can achieve the Pareto improvement of the supply chain, but the revenue sharing contract yields better results in terms of supplier quality level and supply chain members' profit.

Management Insights: 1) For the government, it should actively promote the policy and uphold market regulations to incentivize members of the NEV supply chain to enhance quality and foster the sustainable growth of the NEV industry. 2)Manufacturers should pay attention to the quality cost factor of suppliers and provide effective incentive pacts to improve the quality of R&D under the policy. Especially at high cost coefficients and low points prices, consider using revenue sharing contracts to stimulate supplier motivation.

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