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COORDINATION OF DUAL-CHANNEL SUPPLY CHAIN CONSIDERING DIFFERENTIAL PRICING AND LOSS-AVERSION BASED ON QUALITY CONTROL

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Abstract. This paper investigates the coordination of dual-channel supply chain under quality control with a loss-averse manufacturer and a loss-averse retailer. Facing various uncertain factors, supply chain members tend to show loss aversion, which makes their actual decision deviate from the optimal decision without considering loss aversion. Therefore, the loss aversion effect function is applied to characterize the loss aversion of members. Besides, under quality control, utility model is constructed under centralized decision and decentralized decision, and the optimal decisions are solved according to the principle of utility maximization. Further, by analyzing and comparing the optimal strategies of two typical decision structures, the wholesale price and the quality cost-sharing contract is designed to coordinate the dual-channel supply chain, and the contract is proved to be valid. Finally, the impacts of the parameters change on the optimal quality level and order price are presented through the sensitivity analysis. It is found that quality control strategy and loss aversion degree of supply chain members affect the setting of coordination contract parameters and utility of supply chain. Moreover, the coordination of dual-channel supply chain is conducive to improving the level of product quality and reducing the price difference between channels.

1. **Introduction.** The dual-channel supply chain has been receiving increasing attention in recent years. With the popularity of the Internet, many top suppliers, such as IBM, Cisco, Nike, and Estee Lauder, have started selling directly online. Manufacturers' online sales have directly expanded the market, but there are also

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some quality problems. According to the quality inspection report from Chain Consumers Association, the unqualified rate of goods purchased online reached 23.6%. Product quality control needs to be paid more attention to the dual-channel supply chain. A few scholars have stated that the channel structure of supply chain has an impact on the level of product quality or price. Shi et al. [21] found that the product quality between retail channels and direct channels is affected by the type of distribution function of consumer heterogeneity. Chen et al. [2] demonstrated that the impacts of channel structures on product quality and price, and quality sensitivity parameters of different channels are analyzed. Zhou et al [35] found the consumers of the product quality reference are different on a dual-channel. The loyalty of the consumer to the traditional retail channel affects the service quality of retailers [12]. However, control strategy of product quality has been rarely considered in dual-channel supply chain with differential pricing. In fact, the different channel structures affect supply-chain players' strategic quality and price decisions, and then affect supply chain coordination.

When a company serves as both a supplier and a direct competitor of any existing reseller partners, channel conflict may occur [23]. A dual-channel supply chain with potential channel conflicts is difficult to achieve supply chain coordination. Coordinated decision madding in the dual-channel supply chain plays a vital role in achieving the participants' objectives. An efficient supply chain system seeks to integrate the inbound activities of each supply chain member while taking into account the decisions and activities of other partners [24]. For the decentralized supply chain, many efforts have been made to improve the overall competitiveness through vertical coordination [9]. Moreover, product quality in dual-channel supply chain will have an impact on the coordination decision of the supply chain. This has led to the study of the relationship between quality and coordination in a dual-channel supply chain. Chen et al. [2] proved that quality improvement by manufacturers can alleviate channel conflicts, especially when the market is more sensitive to product quality. Product quality and return are considered in the design of dual-channel coordination mechanism in closed-loop supply chain [33]. In addition, in practice due to costs such as store rents, logistics, and transportation, traditional channels, and online channels may sell goods at different prices. In order to improve product quality, retailers will take some quality control measures, which will also affect the optimal decision-making of supply chain members, and then affect the coordination of dual-channel supply chain. Therefore, this paper raises the question of how to coordinate the dual-channel supply chain with differential pricing under quality control.

Furthermore, fierce competition brings more uncertainty to the market demand. Therefore, supply chain members tend to show the characteristics of loss aversion, which could affect their quality decision-making in practice. Supply chain players always face many kinds of risk, such as volatility of orders, uncertain production cost, and material procurement [26, 27, 30, 36]. However, most of the literature on product quality and coordination of dual-channel supply chains does not consider risk aversion. A few literatures only consider unilateral risk. Risk management needs to balance performance and risk in decision-making process [5]. The decision results are different considering the loss-averse of all the players in the supply chain. The loss aversion leads to the change of supply chain strategy based on the preference theory. Many experimental studies and managerial decision-making practices under uncertainty have asserted that enterprise managers' decision-making behaviors deviate from expected profit maximization due to loss aversion [9]. Therefore, it is crucial to extend the coordination model under quality control in dual-channel supply chain to a quality control coordination model considering both the loss aversion of the manufacturer and the retailer. Considering the behavior preference of supply chain players can make the research closer to reality. The calculated optimal decision of dual-channel supply chain is more in line with the actual situation and can provide reference for the actual decision-making of supply chain members.

Therefore, the contributions of this paper to literature are in the following aspects:

(1) A strategy is proposed to coordinate the decentralized dual-channel supply chain with differential pricing considering loss aversion and quality control. The coordinated decision-making under considering all the players' risk aversion is more in line with the actual situation.

(2) The effects of both loss aversion of the manufacturer and the retailer on coordination mechanism, optimal dual-channel supply chain decisions and utility are examined.

(3) The best quality level of the products and the price difference are analyzed considering retailer's control measures and dual-channel simultaneously.

Based on this, the quality control, price difference, and loss aversion of the players are simultaneously taken into account when exploring the optimal strategies and profitability of dual-channel supply chain in this paper. On the other hand, we propose a coordination mechanism. These research results can provide reference for enterprises in the actual decision-making process. The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 is devoted to model formulation and analysis. We identify equilibrium solutions for centralized decision model and decentralized decision model, and then we coordinated the supply chain by introducing the contract. Numerical examples and discussion of results are presented in Section 4. Finally, conclusions and future research directions are offered in Section 5.

2. **Literature review.** A dual-channel with both retail and direct channels is becoming a popular channel structure. The dual-channel supply chain has drawn widespread attention in the literature, especially with regard to quality and pricing issues. Players' strategies and customer satisfaction levels determine quality management practices [13]. The relation of product quality between the retail channel and the direct channel is determined by the type of distribution function of consumer heterogeneity [21]. Chen et al. [2] demonstrate that quality improvement can be realized when a new channel is introduced. Moreover, the transition from manufacturer to manufacturer-direct could enable a manufacturer to deliver a better quality product at a lower price [19]. The price difference between the two kind of channel attract attention, and the pricing decision in the dual-channel supply chain play an important role. Maiti and Giri [18] investigated the relationship between quality and retail price in the closed-loop supply chain. Chen et al. [2] consider price and quality decisions in a dual-channel supply chain and give the impacts of adding a new channel on price. This study finds the supply chain performance could be improved due to a new channel augmented. However, it is still unclear

what quality control decisions should make when a manufacturer employs a dual-channel supply chain. This paper will focus on quality control in the dual-channel supply chain.

Channel conflict is a difficult problem for the dual-channel supply chain. Then a considerable body of literature has been developed in regard to coordination of dual-channel supply chain. To alleviate the channel conflicts of increasing direct sales channels, Tang et al. [22] studied how to apply revenue sharing contracts to coordinate the dual-channel supply chain with demand and cost interruption. The manufacturer Stackelberg game model is used to examine the manufacturer's pricing strategy in the dual-channel supply chain [3]. Xu et al. [29] considered low-carbon preference and dual-channel conflict, and introduced an improved revenue sharing contract to coordinate the supply chain. Aslani and Heydari [1] designed a transshipment contract to coordinate the green dual-channel supply chain, and considered the pricing problem. Chen et al. [2] found that the product quality under the dual-channel supply chain can be improved by studying the supply chain pricing and quality decision-making under different channels. Subsequently, Zhang et al. [34] investigated the impact of three different contracts on dual-channel supply chain performance, and considered pricing decision of a retailer-dominant supply chain. Zhou et al. [35] focused on the impact of quality reference effect on coordination decision-making in dual-channel supply chain. The above-mentioned coordinator mechanism of dual-channel literature does not focus on quality control strategies and ignores members' attitudes towards dual-channel risks, this paper intends to introduce the quality factor into the coordination mechanism, and consider the risk attitude of supply chain members in decision-making.

In light of the above literature, it is assumed that players in the supply chain are risk neutral. However, by Prospect Theory [11], people are more sensitive to losses than to gains of the same size, this type of decision-making behavior is identified as loss aversion. Many experimental studies and managerial decision-making practices under uncertainty have shown that enterprise managers' decision-making behaviors deviate from expected profit maximization due to loss aversion [4, 7, 8, 20]. Since increases in market demand uncertainty and risk for supply chain, the players are more likely to keep loss averse. Based on the above literature research, it can be seen that existing research results that rely on loss-neutral behavior assumptions may not be applicable to supply chains that include loss-averse participants.

Therefore, it is critical to study the effect of loss aversion on supply chain members' decisions and supply chain performance, under various scenarios. Recently, loss aversion behavior has been applied to supply chain research. Since the optimization decision without considering risk deviates from the actual optimization decision, Felfel et al. [5] extend the stochastic programming model to a risk management multi-objective optimization model. Schweitzer and Cachon [20] found that a loss-averse newsvendor without shortage cost orders strictly lower than a risk-neutral newsstand. Later, channel bargaining with risk aversion retailers was studied [17]. Xu et al. [28] establish a mean-variance model to investigate the impact of dual-channel supply chain considering the risk aversion of the supply chain agents. Liu et al. [15] extended the study of risk aversion to dual-channel supply chain under information and asymmetric information case. They also analyze the impact of risk tolerance on the manufacturer and retailer's pricing decisions. Feng and Tan [6] indicate the impacts of loss aversion on the price, green degree, profits in a two-echelon green supply chain. A few literatures further extend the research

TABLE 1. Comparison of contributions from different relevant literature

Literature	Dual-channel	Coordination	Loss-aversion		Quality		Differential pricing
			One player	Two players	Quality decision	Quality control	
Zhou and Xu [35]	✓	✓			✓		
Huang and He [10]		✓	✓				
Zhang et al. [34]	✓	✓			✓		✓
Xie and Chen [25]		✓	✓				
Zhuo et al. [36]		✓		✓			
Liu and Fan [14]		✓	✓		✓		
This paper	✓	✓		✓	✓	✓	✓

to the impact of risk aversion on dual-channel supply chain coordination. Yang and Xiao [32] found consumers' risk aversion to service quality affect the construction of dual-channel supply chain coordination contract. Xie et al. [25] showed the wholesale price contract unable to achieve the coordinate of supply chain due to the effects of loss aversion. Liu et al. [16] found that the retailer's expected utility, optimal quantity, and coordinated wholesale price are reduced at the level of loss avoidance. Previous studies about coordination of dual-channel supply chain consisted of only one risk-averse decision maker, however, this paper is different from the above researches because both manufacturers and retailers' loss aversion are considered. Moreover, quality control issues are also considered in the coordination mechanism of dual-channel supply chain. Considering the risk degree is a factor that influences decision making in the dual-channel supply chain, therefore, the players' loss aversion is considered when this paper researches the quality control in the dual-channel supply chain. Summary of the related literature regarding coordination and loss-aversion in dual-channel supply chain (Table 1).

In this paper, the effect of the players' loss aversion behaver on their quality control decisions and the price difference between the channels are considered in the dual-channel supply chain. It is necessary to improve the quality of manufactured products in the dual-channel supply chain by taking effective quality control measures. High-quality products can enhance brand equity and the appropriate price difference can keep customers loyal, which is important to maintain the sustainable development of the dual-channel supply chain. Moreover, with the market uncertain factors increasing, the players of the supply chain tend to show loss aversion behavior. This behavior affects the decisions of supply chain members. Thus, it is significant for this paper to research the quality of manufactured products considering the players' loss aversion.

3. Model formulation and analysis.

3.1. Question description and model formulation. This paper considers a dual-channel supply chain with a loss-averse manufacturer and a loss-averse retailer. When manufacturers sell goods to retailers (traditional retail channel), they also sell goods online to consumers directly (online direct channel). Suppose the manufacturer prioritizes the market demand for the direct sales channel, that is, the manufacturer's online sales channel does not have the risk of out-stock. Due to costs such as store rents, logistics, and transportation, traditional channels, and online channels may sell goods at different prices, and the difference is noted by Δp, if Δp=0, it means that the two channels have the same price. if Δp>0, it means higher offline price, and if Δp>0, it means higher online price. The market demand for products is stationary, denoted by $x_i (i = r, d)$. If there is a shortage in sales, the retailer and the manufacturer share the cost of stock-out. At the end of the sales season, the retailer's unsold products will be processed uniformly. The subscripts r and d in the text represent traditional channel and network channel, respectively.

Both the quality and price of products affect their market demand. To expand market share, the retailers and the manufacturers reach an agreement regarding the quality level of the purchases in advance. The retailer controls the quality by inspecting the products purchased from retailers. Manufacturers are required to compensate for the products which do not meet the set quality level, and the retailer pays for the inspection cost. As for the non-conforming products, the retailer directly disposes of them and no longer sells them externally, and the income is denoted m. The retailer's quality control measures promote the manufacturer to improve the product quality level, which also promotes the improvement of the product quality on direct sales channel. Moreover, consumers' online evaluations of product quality affect the sales volume of the online channel.

In order to increase the sales volume, the manufacturer will strive to improve the product quality level, denoted by e, and the effort cost is c_e. According to previous literature [31], we set $c_e = \frac{\eta e^2}{2}$, where η is the quality effort cost coefficient. $G(x_r|e)$ denotes the conditional distribution function of the retailers' market demand, and $g(x_r|e)$ is the corresponding probability density function. $G(x_r|e)$ or $g(x_r|e)$ could reflect the impact of quality on demand. We set the expected demand of the product is μ_i, denoted $E(x_i) = \mu_0$.

According to reference, the demand functions of the traditional channel and the network channel are respectively given by Eqs. (1) and (2):

$$d_r = sa - \theta_r (p + \Delta p) + x_r \tag{1}$$

$$d_d = (1 - s) a - \theta_d p + x_d \tag{2}$$

Where $a(a > 0)$ is the market size; $s\,(0 < s < 1)$ denote the market share of retailers in the traditional channel; $\theta_i\,(i = r, d)$ denoted the coefficient of influence of price on market demand, and $\theta_i > 0$.

The following notations defined in Table 2 are used in this paper:

According to the question description above, the profit function of the risk-neutral manufacturer is given by

$$\pi_M = q(w - c) + d_d (p - c) - qc_c(1 - p_c) - c_d \max\{d_r - qp_c, 0\} - \frac{\eta e^2}{2} \tag{3}$$

The first term and second term denote manufacturer's profit of selling products to manufacturers and selling products directly online; the third term gives the compensation for non-conforming products; the remaining terms consist of two costs, including manufacturer's stock-out cost and quality effort cost.

The profit function of the risk-neutral retailer is

$$\begin{aligned} \pi_R = (p + \Delta p) \min\{dr, qp_c\} + qc_c(1 - p_c) + v \max\{qp_c - d_r, 0\} \\ + m - wq - c_r \max\{d_r - qp_c, 0\} - c_i \end{aligned} \tag{4}$$

The first term denotes retailer's revenue; the second term shows the compensation from the manufacturers; the third term and four terms are the retailer's income from the disposal of unsalable products and non-conforming products respectively; the remaining terms consist of three costs, including products purchase cost, out of stock cost of the retailer, and inspection cost.

TABLE 2. Notations defined

Parameter	Definition
w	the wholesale price
p	online selling price
Δp	the price difference between the online channel and offline channel
c	unit production cost
q	order size of the retailer for the new product
c_r	out of stock cost per unit shortage of the retailer
c_d	out of stock cost per unit shortage of the manufacturer
p_c	qualified products rate
c_i	inspection cost
c_c	unit compensation amount for non-conforming products
m	retailer's income from the disposal of non-conforming products
v	retailer's income from the disposal of unsalable products
e	the product quality level
c_e	quality effort cost
x_r	stochastic demand of the product in the traditional channel
x_d	stochastic demand of the product in the network channel
π_M	profit of the manufacturer under risk-neutral
π_R	profit of the retailer under risk-neutral
$E\pi_M$	expected profit of the manufacturer under risk-neutral
$E\pi_R$	expected profit of the retailer under risk-neutral
$EU(\pi_M)$	the utility of the manufacturer
$EU(\pi_R)$	the utility of the retailer

Eqs. (3) and (4) lead to the expected profit of the risk-neutral manufacturer and the risk-neutral retailer, as follow Eqs. (5) and (6).

$$\begin{aligned} E\pi_M &= q(w - c - c_c(1 - p_c) + c_d p_c) + d_d(p - c) \\ &\quad - c_d\left(\int_A^{\infty} d_r dG(x_r|e) + qp_c G(A|e)\right) - \frac{\eta e^2}{2} \end{aligned} \tag{5}$$

$$\begin{aligned} E\pi_R &= (p + \Delta p - v)\int_0^{A} d_r dG(x_r|e) + q(c_c(1 - p_c) - w) + m - c_i \\ &\quad - c_r\int_A^{+\infty} d_r dG(x_r|e) + qp_c((v - c_r - p - \Delta p)G(A|e) + p + \Delta p + c_r) \end{aligned} \tag{6}$$

where $A = qp_c - sa + \theta_r(p + \Delta p)$.

According to Eq. (5), the demand threshold k_M when the risk-neutral manufacturer's profit is breakeven can be formulated as:

$$k_M = \frac{q(w - c - c_c(1 - p_c) + c_d p_c) - \frac{\eta e^2}{2} + d_d(p - c)}{c_d} \tag{7}$$

From Eq. (6), the two demand thresholds, k_{R1} and k_{R2}, when the risk-neutral retailer reach profit breakeven, can be given by

$$k_{R1} = \frac{q(w - c_c(1 - p_c) - vp_c) + c_i - m}{p + \Delta p - v} \tag{8}$$

$$k_{R2} = \frac{q(p_c(p + \Delta p) - w + c_c(1 - p_c) + c_r p_c) - c_i + m}{c_r} \tag{9}$$

Based on the above, we obtain the result: the manufacturer's profit is negative when $d_r > k_M$. While $d_r < k_{R1}$ or $d_r > k_{R2}$, the retailer's profit becomes negative.

If both manufacturers and retailers want to make a profit, dr should meet both conditions $d_r < k_M$ and $k_{R1} < d_r < k_{R2}$. The utility function of loss aversion is given by

$$\mu(y) = \begin{cases} y - y_0, y \geq y_0 \\ \lambda(y - y_0), y < y_0 \end{cases} \tag{10}$$

where y_0 denotes the initial wealth value, and lets $y_0 = 0$ simplify the calculation. The parameter λ indicates the degree of loss aversion. If $\lambda = 1$, which means the member of the supply chain is risk neutral. If $\lambda > 1$, which shows the member is loss-averse, and the bigger λ becomes, the higher the loss averse is. We assume that retailers and manufacturers show the same degree of loss aversion to simplify the model since they are in the same market environment.

From Eqs. (3) and (7), the expected utility of the loss-averse manufacturer can be expressed as

$$EU(\pi_M) = E\pi_M + (\lambda - 1)\int_{k_M}^{+\infty} \begin{pmatrix} q(w - c - c_c(1 - p_c)) \\ -\frac{\eta e^2}{2} - c_d(d_r - qp_c) + d_d(p - c) \end{pmatrix} dG(x_r|e) \tag{11}$$

According to Eqs. (4), (8) and (9), we obtain the loss-averse retailer's expected utility as following

$$EU(\pi_R) = E\pi_R + (\lambda - 1)\begin{pmatrix} \int_0^{k_{R1}} \begin{pmatrix} d_r(p + \Delta p) - wq + qc_c(1 - p_c) \\ +v(qp_c - d_r) - c_i + m \end{pmatrix} dG(x_r|e) \\ + \int_{k_{R2}}^{+\infty} \begin{pmatrix} p_c q(p + \Delta p) - wq + qc_c(1 - p_c) \\ -c_r(d_r - qp_c) - c_i + m \end{pmatrix} dG(x_r|e) \end{pmatrix} \tag{12}$$

3.2. **Decentralized decision.** In the decentralized case, manufacturers and retailers, as independent economic entities, make respectively optimal choices based on their utility maximization principles. The manufacturer determines the optimal quality level, e^*, according to the law of utility maximization. While the retailer also decides his optimal price difference by maximizing his utility. The first order derivative of Eq. (11) with respect to e is as follows

$$\begin{aligned} \frac{dEU(\pi_M)}{de} = e\eta + (\lambda - 1)&\begin{pmatrix} e\eta(-as + \theta_r g(k_M|e)(p + \Delta p)) \\ + \int_{k_M}^{+\infty}(-e\eta g(x_r|e) + c_d(k_M + d_r))\, d\frac{\partial G(x_r|e)}{\partial e} \end{pmatrix} \\ &- c_d\left(\int_A^{+\infty} d_r d\frac{\partial G(x_r|e)}{\partial e} + qp_c\frac{\partial G(A|e)}{\partial e}\right) \end{aligned} \tag{13}$$

The second order derivative of Eq. (11) with respect to e can be calculated as

$$\begin{aligned} \frac{d^2EU(\pi_M)}{de^2} = -(\lambda - 1)&\begin{pmatrix} \frac{e^2\eta^2 g(k_M|e)}{c_d} + \eta g(k_M|e)(as - \theta_r(p + \Delta p)) \\ + \int_{k_M}^{+\infty}\left(\eta g(k_M|e) + e\eta\frac{\partial g(x_r|e)}{\partial e}\right) d_r \\ + e\eta(as - \theta_r(p + \Delta p))\left(1 + \frac{e\eta}{c_d}\right)\frac{\partial g(k_M|e)}{\partial e} \end{pmatrix} \\ &- c_d\left(\int_A^{+\infty} d_r d\frac{\partial^2 G(A|e)}{\partial e^2} + p_c q\frac{\partial^2 G(A|e)}{\partial e^2}\right) - \eta \end{aligned} \tag{14}$$

Because of $\eta > 0$, $as - \theta_r(p + \Delta p) > 0$, so $\frac{d^2EU(\pi_M)}{de^2}|_{e=e^*} < 0$. It illustrates that $EU(\pi_M)$ is concave in e. The unique optimal quality level, e^*, can be calculated from the equation, $\frac{dEU(\pi_M)}{de}|_{e=e^*} = 0$. At this point, the manufacturer can get the most utility.

The first order derivative of Eq. (12) with respect to Δp is as follows

$$\begin{gathered}\frac{dEU(\pi_R)}{d\Delta p} = qp_c\theta_r\left(p+\Delta p-v+c_r\right)g\left(A\left|e\right.\right)-\theta_r\begin{pmatrix}\left(p+\Delta p-v\right)g\left(A\left|e\right.\right)\\ -c_r\int_A^{+\infty}dG\left(x_r\left|e\right.\right)\end{pmatrix}\\ +\int_0^A d_r dG\left(x_r\left|e\right.\right)-qp_c\left(1-G\left(A\left|e\right.\right)+\left(v-\Delta p-p-c_r\right)\frac{\partial G(A|e)}{\partial\Delta p}\right)\\ +(\lambda-1)\begin{pmatrix}p_cq\left(as-\theta_r\left(p+\Delta p\right)\right)g\left(k_{R2}\left|e\right.\right)+\int_{k_{R2}}^{+\infty}\left(p_cq+c_r\theta_r\right)dG\left(x_r\left|e\right.\right)\\ -B+\int_0^{k_{R1}}\left(d_r-\theta_r\left(p+\Delta p\right)v\theta_r\right)dG\left(x_r\left|e\right.\right)\end{pmatrix}\end{gathered}\tag{15}$$

where $B=\frac{k_{R1}g(k_{R1}|e)(c_cq(1-p_c)-qw+(p+\Delta p)(as-\theta_r(p+\Delta p)+k_{R1})+v(m-c_i+A-k_{R1}))}{p+\Delta p-v}$.

The second order derivative of Eq. (12) with respect to Δp is given by

$$\begin{gathered}\frac{d^2EU(\pi_R)}{d\Delta p^2}=\left(2p_cq-\left(c_r{+}p{+}\Delta p-v\right)\theta_r\right)\theta_r g\left(A\left|e\right.\right)-2\theta_r G\left(A\left|e\right.\right)-2p_cq\frac{\partial G(A|e)}{\partial\Delta p}\\ -(\lambda-1)\begin{pmatrix}\left(3as+k_{R1}-\left(3p+3\Delta p-2v\right)\theta_r+\frac{(m-c_i)(v-1)}{p+\Delta p-v}\right)\frac{k_{R1}}{p+\Delta p-v}g\left(k_{R1}\left|e\right.\right)\\ \frac{p_cq(p_cq+2c_r\theta_r)}{c_r}g\left(k_{R2}\left|e\right.\right)+2\theta_r G\left(k_{R1}\left|e\right.\right)\end{pmatrix}\end{gathered}\tag{16}$$

Because of $\theta_r>0$, $\lambda>1$, $2p_cq-\left(c_r{+}p{+}\Delta p-v\right)\theta_r<0$, $0\le k_{R1}\le A\le k_{R2}$, $0\le G\left(k_{R1}\left|e\right.\right)\le G\left(A\left|e\right.\right)\le G\left(k_{R2}\left|e\right.\right)$, $3as{+}k_{R1}-\left(3p+3\Delta p-2v\right)\theta_r+\frac{(m-c_i)(v-1)}{p+\Delta p-v}\ge 0$, so we can get the equation, $\frac{d^2EU(\pi_R)}{d\Delta p^2}<0$, which means $EU\left(\pi_R\right)$is a strictly convex function for Δp. The unique optimal quality level, Δp^*, can be calculated from the equation, $\frac{dEU(\pi_R)}{d\Delta p}\left|_{\Delta p=\Delta p^*}\right.=0$. At this point, the retailer can get the most utility.

Proposition 1. *As to* $\forall e\in[0,+\infty)$, *there are three situations between loss aversion coefficient and optimal price difference as follows:*

If $-p_cqAg\left(k_{R2}\left|e\right.\right)-B+\left(p_cq+c_r\theta_r\right)\left(1-G\left(k_{R2}\left|e\right.\right)\right)-\theta_r\left(\Delta p+p-v\right)G\left(k_{R1}\left|e\right.\right)+\int_0^{k_{R1}}d_r dG\left(x_r\left|e\right.\right)>0$, *then the optimal price difference increases as the degree of loss aversion increases;*

If $-p_cqAg\left(k_{R2}\left|e\right.\right)-B+\left(p_cq+c_r\theta_r\right)\left(1-G\left(k_{R2}\left|e\right.\right)\right)-\theta_r\left(\Delta p+p-v\right)G\left(k_{R1}\left|e\right.\right)+\int_0^{k_{R1}}d_r dG\left(x_r\left|e\right.\right)=0$, *then optimal price difference does not affect the loss aversion coefficient;*

If $-p_cqAg\left(k_{R2}\left|e\right.\right)-B+\left(p_cq+c_r\theta_r\right)\left(1-G\left(k_{R2}\left|e\right.\right)\right)-\theta_r\left(\Delta p+p-v\right)G\left(k_{R1}\left|e\right.\right)+\int_0^{k_{R1}}d_r dG\left(x_r\left|e\right.\right)<0$, *then the optimal price difference decreases as the degree of loss aversion increases.*

Proof. According to the implicit function theorem:

$$\begin{gathered}\frac{d\Delta p^*}{d\lambda}=-\frac{\frac{d^2EU(\pi_R)}{d\Delta p d\lambda}}{\frac{d^2EU(\pi_R)}{d\Delta p^2}}\left|_{\Delta p=\Delta p^*}\right.\\ =-\frac{-p_cqAg(k_{R2}|e)-B+(p_cq+c_r\theta_r)(1-G(k_{R2}|e))-\theta_r(\Delta p+p-v)G(k_{R1}|e)+\int_0^{k_{R1}}d_r dG(x_r|e)}{\frac{d^2EU(\pi_R)}{d\Delta p^2}\left|_{\Delta p=\Delta p^*}\right.}\end{gathered}\tag{17}$$

Because of $\frac{d^2EU(\pi_R)}{d\Delta p^2}\left|_{\Delta p=\Delta p^*}\right.<0$, the sign of the Eq. (16) is consistent with the equation, $-p_cqAg\left(k_{R2}\left|e\right.\right)-B+\left(p_cq+c_r\theta_r\right)\left(1-G\left(k_{R2}\left|e\right.\right)\right)+\int_0^{k_{R1}}d_r dG\left(x_r\left|e\right.\right)-\theta_r\left(\Delta p+p-v\right)G\left(k_{R1}\left|e\right.\right)$. Therefore, we obtain proposition 1.

This proposition reveals the relationship between the degree of loss aversion and the optimal price difference when the quality level of the product is a certain value. According to the relationship, it can provide guidance for the pricing decision of loss averse retailers. □

Proposition 2. *In the decentralized decision, the optimal response function of product quality level $e\left(\Delta p\right)$ is an increasing function about the price difference Δp and the optimal response function of the price difference $\Delta p\left(e\right)$is an increasing function about quality level e.*

Proof. According to Eqs. (13) and (15), the optimal response functions $e\left(\Delta p\right)$and $\Delta p\left(e\right)$meet Eqs. (18) and (19), respectively. As following:

$$\begin{array}{l} e\eta+(\lambda-1)\left(\begin{array}{l} e\eta\left(-as+\theta_r g\left(k_M\left|e\right.\right)(p+\Delta p)\right)\\ +\int_{k_M}^{+\infty}\left(-e\eta g\left(x_r\left|e\right.\right)+c_d\left(k_M+d_r\right)\right)d\frac{\partial G(x_r|e)}{\partial e} \end{array}\right)\\ -c_d\left(\int_A^{+\infty}d_r d\frac{\partial G(x_r|e)}{\partial e}+qp_c\frac{\partial G(A|e)}{\partial e}\right)=0 \end{array} \tag{18}$$

$$\begin{array}{l} qp_c\theta_r\left(p+\Delta p-v+c_r\right)g\left(A\left|e\right.\right)-\theta_r\left(\left(p+\Delta p-v\right)g\left(A\left|e\right.\right)-c_r\int_A^{+\infty}dG\left(x_r\left|e\right.\right)\right)\\ +(\lambda-1)\left(\begin{array}{l} p_c q\left(as-\theta_r\left(p+\Delta p\right)\right)g\left(k_{R2}\left|e\right.\right)-B+\int_{k_{R2}}^{+\infty}\left(p_c q+c_r\theta_r\right)dG\left(x_r\left|e\right.\right)\\ +\int_0^{k_{R1}}\left(d_r-\theta_r\left(p+\Delta p\right)v\theta_r\right)dG\left(x_r\left|e\right.\right) \end{array}\right)\\ +\int_0^A d_r dG\left(x_r\left|e\right.\right)-qp_c\left(1-G\left(A\left|e\right.\right)+\left(v-\Delta p-p-c_r\right)\frac{\partial G(A|e)}{\partial\Delta p}\right)=0 \end{array} \tag{19}$$

According to the implicit function theorem:

$$\begin{array}{c} \frac{de(\Delta p)}{de}=-\frac{\frac{d^2EU(\pi_M)}{ded\Delta p}}{\frac{d^2EU(\pi_M)}{de^2}}\left|_{\Delta p=\Delta p^*}\right.\\ =-\frac{\theta_r\left((\lambda-1)\left(e\eta g(k_M|e)+c_d\int_{k_M}^{+\infty}\frac{\partial g(x_r|e)}{\partial e}dx_r\right)+c_d\left(\int_A^{+\infty}\frac{\partial g(x_r|e)}{\partial e}dx_r+p_c q\frac{\partial g(A|e)}{\partial e}\right)\right)}{\frac{d^2EU(\pi_M)}{de^2}} \end{array} \tag{20}$$

$$\begin{array}{c} \frac{d\Delta p(e)}{d\Delta p}=-\frac{\frac{d^2EU(\pi_R)}{d\Delta p de}}{\frac{d^2EU(\pi_R)}{d\Delta p^2}}\\ =-\frac{\begin{array}{l}\int_0^A d_r d\frac{\partial G(x_r|e)}{\partial e}+(\lambda-1)\left(C-B'\right)+c_r\theta_r\int_A^{+\infty}d\frac{\partial G(x_r|e)}{\partial e}\\ -\theta_r\left(\Delta p+p-v\right)\int_0^A d\frac{\partial G(x_r|e)}{\partial e}-p_c q\left(\frac{\partial G(A|e)}{\partial e}+\left(\Delta p+p+c_r-v\right)\frac{\partial^2 G(A|e)}{\partial e^2}\right)\end{array}}{\frac{d^2EU(\pi_R)}{d\Delta p^2}} \end{array} \tag{21}$$

where

$$\begin{array}{c} C=\left(p_c q+c_r\theta_r\right)\int_{k_{R2}}^{+\infty}d\frac{\partial G(x_r|e)}{\partial e}+\theta_r\left(A-\left(\Delta p+p-v\right)\right)\int_0^{k_{R1}}d\frac{\partial G(x_r|e)}{\partial e}\\ -p_c q\left(\theta_r\left(\Delta p+p\right)-as\right)\frac{\partial g(k_{R2}|e)}{\partial e} \end{array},$$

and

$$B'=\frac{k_{R1}}{p+\Delta p-v}\frac{\partial g\left(k_{R1}\left|e\right.\right)}{\partial e}\left(\begin{array}{l} c_c q\left(1-p_c\right)-qw+v\left(m-c_i+A-k_{R1}\right)\\ +\left(p+\Delta p\right)\left(as-\theta_r\left(p+\Delta p\right)+k_{R1}\right) \end{array}\right).$$

The simplification Eq. (21) can be obtained as follows: $\frac{d\Delta p(e)}{d\Delta p}=-\frac{\frac{d^2EU(\pi_R)}{d\Delta p de}}{\frac{d^2EU(\pi_R)}{d\Delta p^2}}=-\frac{\left(\int_0^A d_r d\frac{\partial G(x_r|e)}{\partial e}+(\lambda-1)\left(C-B'\right)+c_r\theta_r-(p_c q+(p+\Delta p-v+c_r)\theta_r)\frac{\partial G(A|e)}{\partial e}\right)}{\frac{d^2EU(\pi_R)}{d\Delta p^2}}$. Because of $p>\nu$, $\theta_i>0$, $\lambda>1$, $C-B'>0$, so $\frac{de(\Delta p)}{de}>0,\frac{d\Delta p(e)}{d\Delta p}>0$. □

This proposition represents that the price difference of the channel increases along with the increasing quality level of products. As the manufacturer's optimal quality level increases, the price difference between the retail channel and the online channel also expands. This shows that the improvement of the quality level has different effects on the pricing of the dual-channel, and expands the price difference between the two channels. In reality, manufacturers often have a price advantage in the direct channel, which can increase the sales volume of the online channel and the profit of the manufacturer. It shows that the quality control strategy in this paper can effectively promote the manufacturer to improve the quality level. Supply chain members can adjust the pricing of different channels appropriately according to the changes in product quality level.

In the decentralized decision, the manufacturer's optimal quality level, e^*, and the retailer's optimal price difference Δp^* are the solutions of the equations formed by Eqs. (18) and (19), it's given by

$$\begin{cases} e = \dfrac{(\lambda-1)\left(\int_{k_M}^{+\infty}(-e\eta g(x_r|e)+c_d(k_M+d_r))d\frac{\partial G(x_r|e)}{\partial e}\right)-c_d\left(\int_A^{+\infty}d_r d\frac{\partial G(x_r|e)}{\partial e}+qp_c\frac{\partial G(A|e)}{\partial e}\right)}{-\eta(1+(\lambda-1)(-as+\theta_r g(k_M|e)(p+\Delta p)))} \\ G(A|e) = \frac{1}{qp_c}\begin{pmatrix} qp_c+\theta_r\left((p+\Delta p-v)\,g(A|e)+c_r\int_A^{+\infty}dG(x_r|e)\right) \\ -(p+\Delta p-v+c_r)\,qp_c\theta_r g(A|e)-\int_0^A d_r dG(x_r|e) \\ -qp_c(p+\Delta p-v+c_r)\frac{\partial G(A|e)}{\partial \Delta p} \\ +(\lambda-1)\begin{pmatrix} -p_c q(as-\theta_r(p+\Delta p))\,g(k_{R2}|e) \\ -\int_{k_{R2}}^{+\infty}(p_c q+c_r\theta_r)\,dG(x_r|e) \\ -\int_0^{k_{R1}}(d_r-\theta_r(p+\Delta p)v\theta_r)\,dG(x_r|e)+B \end{pmatrix} \end{pmatrix} \end{cases} \tag{22}$$

3.3. **Centralized decision.** For the centralized situation, i.e., the manufacturer and the retailer play as a single entity. In the centralized case, manufacturers and retailers make the optimal strategy together to maximize the utility of the supply chain, which means a whole decides the decisions of quality level and the price difference. The solution of a centralized decision can be used as a benchmark in evaluating total profits. In this decision, the profit of the integrated supply chain is determined by:

$$\begin{aligned} \pi = {} & d_d(p-c)+(p+\Delta p)\min\{d_r,qp_c\}+v\max\{qp_c-d_r,0\} \\ & -(c_d+c_r)\max\{d_r-qp_c,0\}-qc-\frac{\eta e^2}{2}-c_i+m \end{aligned} \tag{23}$$

According to Eq. (23), the expected profit of the supply chain in the centralized decision is given by

$$\begin{aligned} E\pi = {} & d_d(p-c)-qc+(p+\Delta p-v+c_d+c_r)\int_0^A d_r dG(x_r|e)+vqp_c G(A|e) \\ & -\frac{\eta e^2}{2}-c_i+m+qp_c(c_d+c_r+p+\Delta p)(1-G(A|e))-c_d-c_r \end{aligned} \tag{24}$$

From Eq. (24), the two demand thresholds, k_1 and k_2, when the risk-neutral integrated supply chain reaches profit breakeven, can be given by

$$k_1 = \frac{q(c-vp_c)-d_d(p-c)+\frac{\eta e^2}{2}+c_i-m}{(p+\Delta p-v)} \tag{25}$$

$$k_2 = \frac{d_d(p-c)+qp_c(p+\Delta p+c_d+c_r)-qc-\frac{\eta e^2}{2}-c_i+m}{c_d+c_r} \tag{26}$$

Considering Eqs. (24), (25) and (26), the expected utility of the loss averse supply chain is

$$EU(\pi) = E\pi + (\lambda - 1)\left(\begin{array}{c} \int_0^{k_1}\left(\begin{array}{c} d_d(p-c) - qc - \frac{\eta e^2}{2} - c_i + m \\ +(p+\Delta p)d_r + v(qp_c - d_r) \end{array}\right) dG(x_r|e) \\ +\int_{k_2}^{+\infty}\left(\begin{array}{c} d_d(p-c) - qc - \frac{\eta e^2}{2} - c_i + m \\ +(p+\Delta p)qp_c - (c_d + c_r)(d_r - qp_c) \end{array}\right) dG(x_r|e) \end{array}\right) \tag{27}$$

In the centralized decision, the manufacturer's optimal quality level, e_c^*, and the retailer's optimal price difference Δp_c^* are the solutions of the equations as follows:

$$\begin{cases} e = \dfrac{\begin{array}{c} (p+\Delta p + c_d + c_r - v)\left(\int_0^A d_r d\frac{\partial G(x_r|e)}{\partial e} - p_c q\frac{\partial G(A|e)}{\partial e}\right) \\ +(\lambda-1)\left(\begin{array}{c} \int_{k_2}^{+\infty}(-e\eta g(x_r|e) + (c_d+c_r)(k_1 - d_r))d\frac{\partial G(x_r|e)}{\partial e} \\ +\int_0^{k_1}(-e\eta g(x_r|e) + (p+\Delta p - v)(d_r - k_1))d\frac{\partial G(x_r|e)}{\partial e} \end{array}\right) \end{array}}{-\eta(-1+(\lambda-1)(as-\theta_r(p+\Delta p))(g(k_1|e)-g(k_2|e)))} \\ G(A|e) = \dfrac{\left(\begin{array}{c} qp_c(1+(p+\Delta p - v + c_d + c_r)\theta_r g(A|e)) \\ +\int_0^A d_r dG(x_r|e) - (p+\Delta p + c_d + c_r - v)qp_c\frac{\partial G(x_r|e)}{\partial \Delta p} \\ +(\lambda-1)\left(\begin{array}{c} (-as+\theta_r(p+\Delta p))(k_1 g(k_1|e) - p_c q g(k_2|e)) \\ +(p_c q + (c_d+c_r)\theta_r)(1-G(k_2|e)) + \int_0^{k_1} d_r dG(x_r|e) \end{array}\right) \end{array}\right)}{qp_c + (p+\Delta p + c_d + c_r - v)\theta_r} \end{cases} \tag{28}$$

Proposition 3. *The dual-channel supply chain cannot achieve coordination in the decentralized under products' quality control and considering the loss aversion of the members of the supply chain.*

Proof. Assuming the dual-channel supply chain can get coordination, the following conditions can be met: $e^* = e_c^*$ and $\Delta p^* = \Delta p_c^*$. Supposing $e^* = e_c^*$, we can obtain the following equation according to Eqs. (22) and (28):

$$\begin{array}{c} \dfrac{\left(\begin{array}{c} (p+\Delta p + c_d + c_r - v)\left(\int_0^A d_r d\frac{\partial G(x_r|e)}{\partial e} - p_c q\frac{\partial G(A|e)}{\partial e}\right) \\ +(\lambda-1)\left(\begin{array}{c} +\int_{k_2}^{+\infty}(-e\eta g(x_r|e) + (c_d+c_r)(k_1-d_r))d\frac{\partial G(x_r|e)}{\partial e} \\ +\int_0^{k_1}(-e\eta g(x_r|e) + (p+\Delta p - v)(d_r - k_1))d\frac{\partial G(x_r|e)}{\partial e} \end{array}\right) \end{array}\right)}{-\eta(-1+(\lambda-1)(as-\theta_r(p+\Delta p))(g(k_1|e)-g(k_2|e)))} \\ = \dfrac{\left(\begin{array}{c} (\lambda-1)\left(\int_{k_M}^{+\infty}(-e\eta g(x_r|e) + c_d(k_M + d_r))d\frac{\partial G(x_r|e)}{\partial e}\right) \\ -c_d\left(\int_A^{+\infty} d_r d\frac{\partial G(x_r|e)}{\partial e} + qp_c\frac{\partial G(A|e)}{\partial e}\right) \end{array}\right)}{-\eta(1+(\lambda-1)(-as+\theta_r g(k_M|e)(p+\Delta p)))} \end{array} \tag{29}$$

For $\lambda = 1$, we can get $\frac{(p+\Delta p+c_d+c_r-v)}{c_d} + 1 = \frac{\int_{-\infty}^{+\infty} d_r d\frac{\partial G(x_r|e)}{\partial e}}{\left(\int_0^A d_r d\frac{\partial G(x_r|e)}{\partial e} - qp_c\frac{\partial G(A|e)}{\partial e}\right)}$.

Because of $\frac{(p+\Delta p+c_d+c_r-v)}{c_d} \geq 0$, $\int_{-\infty}^{+\infty} d_r d\frac{\partial G(x_r|e)}{\partial e} \geq 0$, so the following formula is established: $\int_0^A d_r d\frac{\partial G(x_r|e)}{\partial e} - qp_c\frac{\partial G(A|e)}{\partial e} < 0$, $\frac{(p+\Delta p+c_d+c_r-v)}{c_d} + 1 \neq \frac{\int_{-\infty}^{+\infty} d_r d\frac{\partial G(x_r|e)}{\partial e}}{\left(\int_0^A d_r d\frac{\partial G(x_r|e)}{\partial e} - qp_c\frac{\partial G(A|e)}{\partial e}\right)}$. Therefore, the assumption above is not true. For $\lambda \neq 1$, it can be proved by the same method. □

We get the conclusion that the dual-channel supply chain cannot achieve coordination in the decentralized decision under products' quality control and considering the loss-averse behavior of the members of the supply chain.

3.4. **Introducing contract.** Based on the above analysis, the dual-channel supply chain can not achieve coordination in the decentralized decision. To coordinate the supply chain, a wholesale price and quality cost-sharing contract with the parameter (w_r, ε) is proposed. In this contract, the retailer will share the effort quality cost of manufacturers, and the share ratio is $(1-\varepsilon)(0<\varepsilon<1)$. Meanwhile, the manufacturer will provide a lower wholesale price to the retailer, and they will bear ε times of the effort quality cost. The utility functions of the manufacturer and the retailer under the contract are given by

$$EU(\pi_{Mq}) = E\pi_{Mq} + (\lambda-1)\int_{k_{Mq}}^{+\infty}\begin{pmatrix} q(w_r-c-c_c(1-p_c)) - \varepsilon\frac{\eta e^2}{2} \\ -c_d(d_r-qp_c)+d_d(p-c) \end{pmatrix} dG(x_r|e) \tag{30}$$

$$EU(\pi_{Rq}) = E\pi_{Rq} + (\lambda-1)\begin{pmatrix} \int_0^{k_{Rq1}}\begin{pmatrix} d_r(p+\Delta p)-w_rq \\ +qc_c(1-p_c)+v(qp_c-d_r) \\ -c_i+m-(1-\varepsilon)\frac{\eta e^2}{2} \end{pmatrix} dG(x_r|e) \\ +\int_{k_{Rq2}}^{+\infty}\begin{pmatrix} p_cq(p+\Delta p)-w_rq \\ +qc_c(1-p_c)-c_r(d_r-qp_c) \\ -c_i+m-(1-\varepsilon)\frac{\eta e^2}{2} \end{pmatrix} dG(x_r|e) \end{pmatrix} \tag{31}$$

In the decentralized decision after introducing contract, the optimal quality level e_q^* and the optimal price difference of channel Δp_p^* are met the following equation:

$$\begin{cases} e = \dfrac{(\lambda-1)\left(\int_{k_{Mq}}^{+\infty}\left(-e\eta g(x_r|e)+c_d\left(k_{Mq}+d_r\right)\right)d\frac{\partial G(x_r|e)}{\partial e}\right)-c_d\left(\int_A^{+\infty}d_rd\frac{\partial G(x_r|e)}{\partial e}+qp_c\frac{\partial G(A|e)}{\partial e}\right)}{-\varepsilon\eta\left(1+(\lambda-1)\left(-as+\theta_rg\left(k_{Mq}|e\right)(p+\Delta p)\right)\right)} \\ G(A|e) = \dfrac{\begin{pmatrix} qp_c-(p+\Delta p-v+c_r)qp_c\theta_rg(A|e) \\ +\theta_r\left((p+\Delta p-v)g(A|e)+c_r\int_A^{+\infty}dG(x_r|e)\right) \\ -qp_c(p+\Delta p-v+c_r)\frac{\partial G(A|e)}{\partial\Delta p}-\int_0^A d_rdG(x_r|e) \\ +(\lambda-1)\begin{pmatrix} -p_cq(as-\theta_r(p+\Delta p))g(k_{Rq2}|e)+B \\ -\int_{k_{Rq2}}^{+\infty}(p_cq+c_r\theta_r)dG(x_r|e) \\ -\int_0^{k_{Rq1}}(d_r-\theta_r(p+\Delta p)v\theta_r)dG(x_r|e) \end{pmatrix} \end{pmatrix}}{qp_c} \end{cases} \tag{32}$$

Proposition 4. *The wholesale price and quality cost-sharing contract can make the dual-channel supply chain coordinated considering quality control and members' loss aversion, under the following condition:*

$$\begin{cases} \varepsilon = \dfrac{D(-1+(\lambda-1)(as-\theta_r(p+\Delta p))(g(k_1|e)-g(k_2|e)))}{\left(1+(\lambda-1)\left(-as+\theta_rg\left(k_{Mq}|e\right)(p+\Delta p)\right)\right)} \\ w_r = \dfrac{\left(-E(p+\Delta p-v)+k_{R1}g(k_{R1}|e)\begin{pmatrix} c_cq(1-p_c)+v(m-c_i+A-k_{R1}) \\ +(p+\Delta p)(as-\theta_r(p+\Delta p)+k_{R1}) \end{pmatrix}\right)}{q} \end{cases} \tag{33}$$

where $w_r\in(0,p)$, Δp_q^* *and* e_q^* *are met Eqs. (29) and (32) at the same time.*

$$D = \frac{\left((\lambda-1)\left(\int_{k_{Mq}}^{+\infty}\left(-e\eta g(x_r|e)+c_d\left(k_{Mq}+d_r\right)\right)d\frac{\partial G(x_r|e)}{\partial e}\right)-c_d\left(\int_A^{+\infty}d_rd\frac{\partial G(x_r|e)}{\partial e}+qp_c\frac{\partial G(A|e)}{\partial e}\right)\right)}{\begin{pmatrix} (p+\Delta p+c_d+c_r-v)\left(\int_0^A d_rd\frac{\partial G(x_r|e)}{\partial e}-p_cq\frac{\partial G(A|e)}{\partial e}\right) \\ +(\lambda-1)\begin{pmatrix} +\int_{k_2}^{+\infty}(-e\eta g(x_r|e)+(c_d+c_r)(k_1-d_r))d\frac{\partial G(x_r|e)}{\partial e} \\ +\int_0^{k_1}(-e\eta g(x_r|e)+(p+\Delta p-v)(d_r-k_1))d\frac{\partial G(x_r|e)}{\partial e} \end{pmatrix} \end{pmatrix}},$$

TABLE 3. Comparison of different decision-making cases

	(w,ε)	Δp	e	$EU(\pi_R)$	$EU(\pi_M)$	$EU(\pi)$
Centralized decision	—	-32.00	13.00	—	—	1564.00
Decentralized decision	(30,—)	13.25	11.07	667.20	150.10	817.31
Introduction contract	(15.84,0.30)	-32.00	13.00	1392.50	171.50	1564.00

$$E = \frac{1}{\lambda-1}\left(\begin{array}{l} \dfrac{qp_c\left(\begin{array}{l} qp_c\left(1+\left(p+\Delta p-v+c_d+c_r\right)\theta_r g\left(A\left|e\right.\right)\right) \\ +\int_0^A d_r dG\left(x_r\left|e\right.\right)-\left(p+\Delta p+c_d+c_r-v\right)qp_c\frac{\partial G\left(x_r\left|e\right.\right)}{\partial \Delta p} \\ +\left(\lambda-1\right)\left(\begin{array}{l} \left(-as+\theta_r\left(p+\Delta p\right)\right)\left(k_1 g(k_1\left|e\right.)-p_c q g(k_2\left|e\right.)\right) \\ +\left(p_c q+\left(c_d+c_r\right)\theta_r\right)\left(1-G\left(k_2\left|e\right.\right)\right) \\ +\int_0^{k_1} d_r dG\left(x_r\left|e\right.\right) \end{array}\right) \end{array}\right)}{qp_c+\left(p+\Delta p+c_d+c_r-v\right)\theta_r} \\ -\left(\begin{array}{l} qp_c-\left(p+\Delta p-v+c_r\right)qp_c\theta_r g\left(A\left|e\right.\right) \\ -qp_c\left(p+\Delta p-v+c_r\right)\frac{\partial G\left(A\left|e\right.\right)}{\partial \Delta p} \\ +\theta_r\left(\begin{array}{l} \left(p+\Delta p-v\right)g\left(A\left|e\right.\right) \\ +c_r\int_A^{+\infty} dG\left(x_r\left|e\right.\right) \end{array}\right)-\int_0^A d_r dG\left(x_r\left|e\right.\right) \\ +\left(\lambda-1\right)\left(\begin{array}{l} -p_c q\left(as-\theta_r\left(p+\Delta p\right)\right)g\left(k_{Rq2}\left|e\right.\right) \\ -\int_{k_{Rq2}}^{+\infty}\left(p_c q+c_r\theta_r\right)dG\left(x_r\left|e\right.\right) \\ -\int_0^{k_{Rq1}}\left(d_r-\theta_r\left(p+\Delta p\right)v\theta_r\right)dG\left(x_r\left|e\right.\right) \end{array}\right) \end{array}\right) \end{array}\right).$$

Proof. According to the definition of supply chain coordination, we can get $e_q^* = e_c^*$ and $\Delta p_q^* = \Delta p_c^*$, based on Eqs. (29) and (32), Eq. (33) can be given. Solving ε and w_r from Eq. (33), we have Eq. (32). In addition, it can be seen from the above formula that quality control and the risk aversion of supply chain members will affect the setting of contract parameters. □

4. **Numerical analysis.** In this section, the performance of the proposed model is illustrated using a numerical example. To better visualize the behavior of the proposed model, a set of sensitivity analyses on some parameters of models are conducted. Meanwhile, the effect of parameters on the supply chain members' optimal policies, under the decentralized and centralized decision, is presented through the sensitivity analysis of the parameters which include λ, e, Δp, and so on. In addition, we verify the theoretical results derived in Section 3 by using several numerical examples. According to the literature [14], to simplify the calculation, we assume retailers' demand function: $x_r = \beta_r e^{1/2} + \delta_r$, where stochastic variable δ_r obeys the uniform distribution on [0,100], and manufacturers' demand function of online direct channel: $x_d = 5e^{1/2} + 40$. The simulation data used for carrying out these numerical computations are assumed to represent real-world conditions as closely as possible. We conducted several groups of simulations and chose a set of representative results in this paper, where the data are set as follows: $p = 40$, $w = 30$, $c = 17$, $c_r = 4$, $c_d = 1$, $c_c = 8$, $\nu = 10$, $\lambda = 1.5$, $a = 150$, $s = 0.6$, $p_c = 0.9$, $\theta_r = 1$, $\theta_d = 0.5$, $\eta = 50$, $\beta_r = 1$, $c_i = 30$, $m = 4$.

4.1. **Analysis of the contract.** According to the established model above, we calculate the optimal decision variables, utilities, and contract parameters in the cases of the centralized decision, decentralized decision, and introduction contract in the decentralized decision. The specific results are shown in Table 3.

Table 3 shows that the dual-channel supply chain can achieve coordination after the introduction of the wholesale price and quality cost-sharing contract. In the case of a decentralized decision, due to the double marginal effect, the retailer's sales price is higher than the manufacturer's online channel, and the price difference between the two channels is 13.25. After the introduction of the contract, the retailer bears 6% quality effort costs of the manufacturer, while the manufacturer sells the product to the retailer at lower wholesale prices. In this way, the expected utility of the supply chain is equal to the utility under a centralized decision by the cooperation of retailers and manufacturers. The retailer's sales price is lower than the manufacturer's online channel, and the price difference between the two channels is expanded to 32.00. Compared with the decentralized decision, the quality level of the product increases from 11.07 to 13.00 under concentration, increasing by 17.43% times. At the same time, the retailer's expected utility improves by 1.09 times, and the manufacturer's expected utility increases by 14.26%. The utility of the supply chain is added to 1564.00, which improves by 91.36% compared with the decentralized decision. Therefore, the introduction of the wholesale price and quality cost-sharing contract not only enhances the optimal quality level and price difference but also improves the expected utility of manufacturers, retailers, and supply chain.

4.2. **Sensitivity analysis of the parameters.** The sensitivity of some useful parameters such as λ, p, s, and p_c on the optimal decision variables as well as the optimal utility of the players involved and the entire supply chain system are investigated. Figs.1-6 reflect the computational results. The following observations are made from the sensitivity analysis.

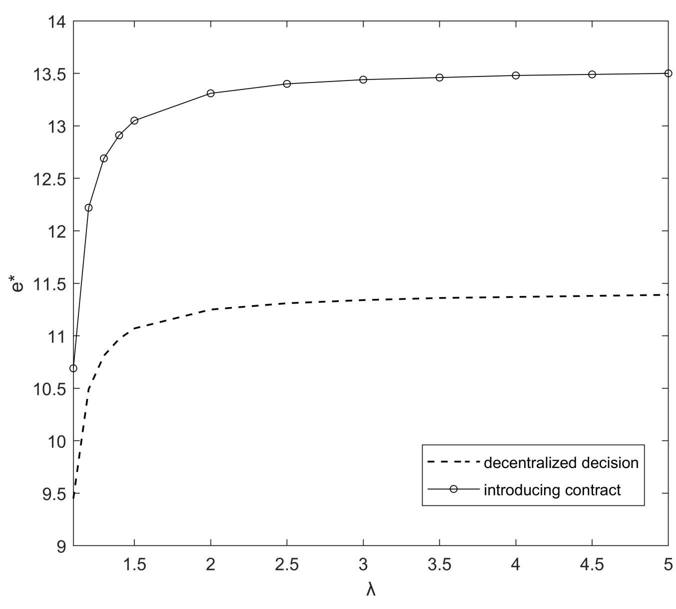

FIGURE 1. Relationship between λ and e^*

Fig.1 and Fig.2 represent the sensitivity analysis of the loss aversion degree and sales price on the optimal quality level. Fig.1 illustrates the relationship between

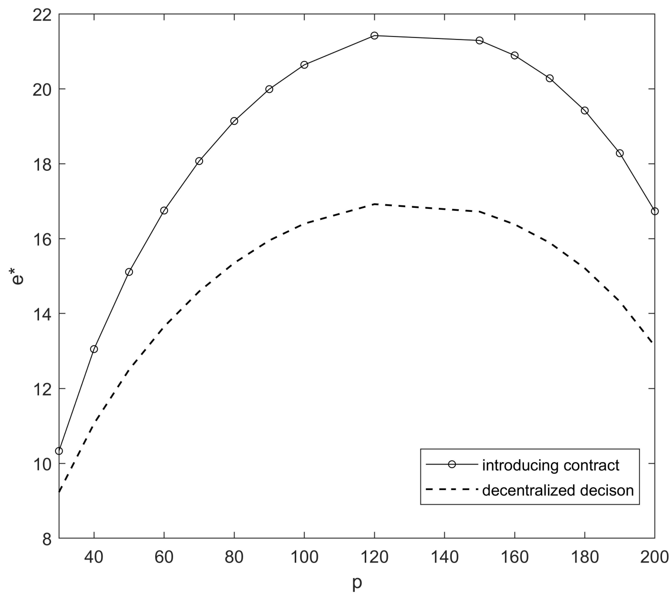

FIGURE 2. Relationship between p and e^*

the degree of loss aversion and the optimal quality level. The two curves of decentralized decision and introducing contract decision show a trend of rising first and then steadily in Fig.1, which means the optimal quality level increase as the degree of loss aversion increases. However, when the degree of loss aversion reaches a specific value (here 1.5), its influence on the optimal quality level is weakened gradually. This shows that the degree of loss aversion of manufacturers and retailers has a significant impact on the optimal quality level within a specific range of values, but after exceeding the certain range, there is almost no impact. In addition, the optimal quality level is higher after introducing contract than that in the decentralized decision when the degree of the loss aversion is the same, indicating that the introduction of the contract is conducive to improving the product quality level.

Fig.2 represents the variation of the optimal quality level with the price online channel. As the price of online channels increases, the optimal quality level shows a trend of rising first and then falling. This shows that high price always represents good quality, but when the sales price is too high (beyond its production cost), the quality level will not increase. The optimal quality level shows the same trend no matter if the contract is introduced. The quality level after the introduction of the contract is higher than that before. In addition, the distance between the curves increases with the price rising, indicating that compared with the low-priced product, the introduction of the contract is more conducive to improving the quality of high-priced products.

The market share of retailers in the traditional channel has an impact on the quality level and the price difference of the two channels. The sensitivity analysis of the market share on the optimal decision variables is shown in Figs.3-4. It

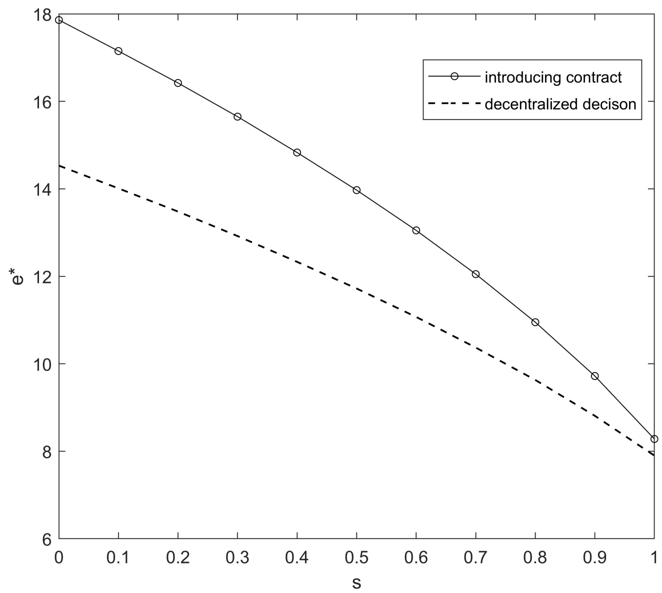

FIGURE 3. Relationship between s and e^*

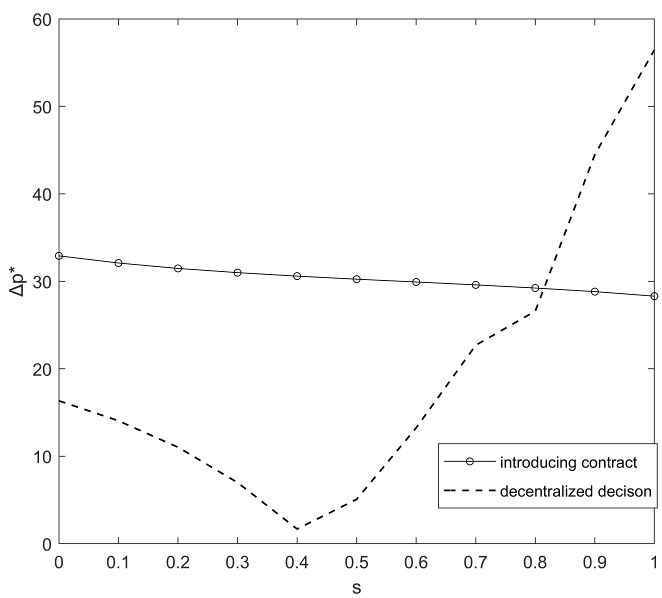

FIGURE 4. Relationship between s and Δp^*

can be seen from Fig.3 that the optimal quality level shows a downward trend with the market share increasing. In turn, this indicates the increase in market share contributes to the improvement of product quality. With the opening of the network channel, manufacturers have more opportunities to understand the quality needs of consumers, which helps improve product quality. In addition, after the contract is introduced, the optimal quality level curve is higher than before, indicating the contract weakens the effect of market share on the optimal quality level. However, as the market share continues to increase, the impact of the contract is also weakening. The distance between the two curves is continuously shortening. Fig.4 shows the relationship between the market share and the price difference between the two channels. We know before the introduction of the contract, the optimal price difference gradually decreases with the increase of the retailer's market share, but when the contract is introduced, the optimal price difference decreases slightly with the increase of market share. If $s < 0.8$, the price difference after the introduction of the contract is greater than before, and the price difference fluctuates greatly before the contract is used. If $s > 0.8$, the curve before the introduction of the contract is higher than it after, indicating that the contract plays a certain role in stabilizing the price difference between channels.

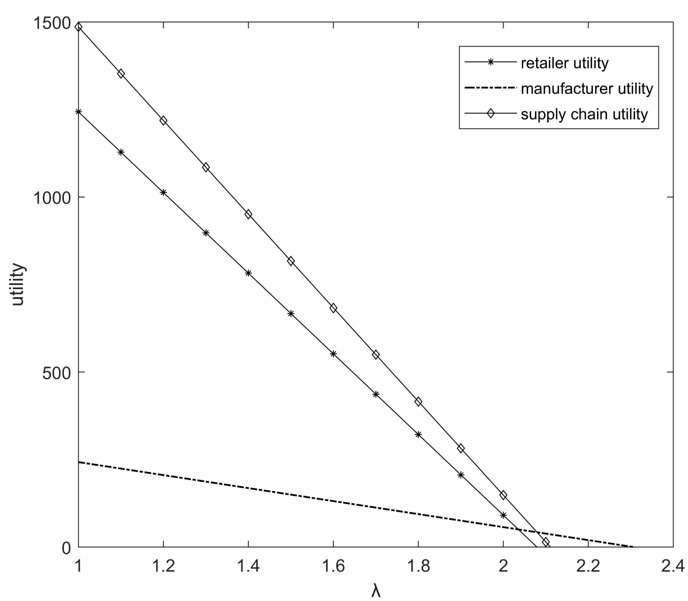

FIGURE 5. Relationship between λ and utility

Figs.5-6 show the impact of loss aversion and qualified products rate on the utility of manufacturers, retailers, and supply chains, respectively. Fig.5 reflects the utility of retailers, manufacturers, and supply chain decrease as the degree of loss aversion increases. Further, from the rate of change of the curve, the retailer's utility curve is steeper while the manufacturer's utility curve is gradual, indicating that the retailer's utility is more sensitive to the change in the degree of loss aversion. The

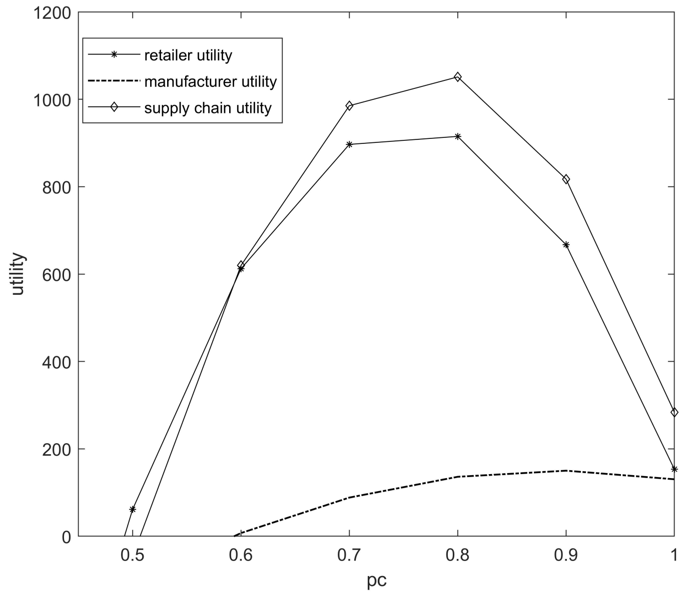

FIGURE 6. Relationship between p_c and utility

effect of loss aversion on the manufacturer's utility is relatively less than the impact on the retailer.

As Fig.6 showns, in addition to the increased utility of manufacturers as the qualified products rate increases, the utility of retailers and supply chains have increased first and then decreased. It means there is an optimal qualified product rate for retailers. If the pass rate is too high, the retailer will reduce its utility due to excessive inspection costs. So the retailer should appropriately adjust the product quality level which was set in advance with the manufacturer according to the change of qualified products rate, to find the optimal rate to improve their utility. As to manufacturers, they can improve their utility by increasing qualified products rate. It also means that the retailer's inspection of the product helps manufacturers to provide products that meet the quality requirements.

5. **Conclusions.** This paper explores the coordination of a dual-channel supply chain under quality control with loss-averse manufacturers and retailers, and generates several findings: first, the introduction of the wholesale price and the quality cost-sharing contract improves the optimal decisions including optimal product quality level and the price difference, which can increase the utility of manufacturers and retailers under decentralized decisions. Further, the coordination of the dual-channel supply chain is realized when the utility of a decentralized supply chain is equal to the level of centralized decision-making by using the contract. Quality control measures and loss avoidance degree of supply chain members affect the setting of coordination contract parameters. The coordination of dual-channel supply chain is conducive to improving product quality, and compared with low price products, the contract is more conducive to improving the quality of high price products.

Second, the increase in manufacturers' market share contributes to the improvement of product quality. In addition, the indication of the contract weakens the effect of retailers' market share on the optimal quality level. The degree of loss aversion of manufacturers and retailers has a significant impact on the optimal quality level within a specific range of values, but after exceeding the certain range, there is almost no impact. The optimal price difference gradually decreases with the increase of the retailer's market share, but when the contract is introduced, the optimal price difference decreases slightly with the increase of market share. Contract plays a certain role in stabilizing the price difference between channels.

Third, the utility of retailers, manufacturers, and supply chains decreases as the degree of loss aversion increases. Besides, the retailer's utility is more sensitive to the change in the degree of loss aversion. Additionally, manufacturers can improve their utility by increasing qualified products rate. It also means that the retailer's inspection of the product helps manufacturers to provide products that meet the quality requirements. Generally speaking, the value of decision variables under centralized decision is greater than it under decentralized decision.

In real life, the asymmetric information phenomenon is widespread and the supply chain hierarchy is more complicated. Future research may focus on the coordination of the multi-level dual-channel supply chain considering quality control and loss avoidance under information asymmetry.

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