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Supply chain game analysis based on mean-variance and price risk aversion under different power structures

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A B S T R A C T

In view of the random retail price and retailer's preference for retail price risk aversion, we used mean-variance to describe the uncertainty risk of retail price. To study the impacts of both the retail price uncertainty risk and retail price risk aversion preference on supply chain (SC) decision-making, we constructed a SC game model based on three different power structures, including Manufacturer Stackelberg (MS) game, Retailer Stackelberg (RS) game, and Vertical Nash (VN) game. The results showed that the retail price uncertainty risk and the retailer's retail price risk aversion preference weakened the manufacturer's production effort input, decreased the retailer's enthusiasm for ordering, and damaged the interests of manufacturer and retailer. Under the three different power structures, the production effort input of the manufacturer depended on the production effort affecting wholesale price efficiency and retail price efficiency. The retailer's expected utility was largest under the MS game model and smallest under the VN game model. The manufacturer's profits were closely related to each parameter under the three respective power structures. This study provides theoretical guidance for the decision-making of SC enterprises with retail price risk and retailer with retail price risk aversion preference under different power structure situations.

A R T I C L E   I N F O

Keywords:
Supply chain game;
Mean-variance;
Retail price risk aversion;
Different power structures;
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Vertical Nash game;
Retailer Stackelberg game;
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1. Introduction

Product market prices are often affected by various factors, which means they are uncertain [1-2]. For example, the Russian-Ukrainian conflict has influenced higher prices for food, oil, and gas across the globe. Additionally, the US trade war has prompted price increases for domestic electronic products, clothing, and furniture. In 2013, the avian influenza A(H7N9) emerged in China, thus decreasing the price of poultry meat [3]. Given the continuous potential for life events such as these, we cannot accurately predict market prices. This seriously impacts decision makers when dealing with issues such as ordering, pricing, and production input. Faced with market price uncertainty risk, different decision makers may also exhibit different behavioral preference; for example, some will adopt risk neutral positions because they are not sensitive to market price uncertainty risk, while others will adopt risk averse positions for the opposite reason. In this context, it is of great practical and theoretical significance to study the SC decision-making problem based on market price uncertainty and market price risk aversion preference among decision makers.

At present, most studies on risk aversion preference have focused on solving decision-making and coordination problems in the SC, as follows:

(1) Decision-making problems under risk aversion preference. Liu *et al*. [4] analyzed how risk aversion affects pricing decisions in the context of competition and information asymmetry. Zhou *et al*. [5] considered optimal advertising investments and ordering decisions when the bilateral parties have risk aversion preference. Targeting cases of demand risk caused by uncertainty in customer valuation, Li and Qi [6] discussed optimal product pricing and quality decisions among risk-averse enterprises. Other scholars have focused on issues such as pricing decisions with consumers' channel preference [7], pricing decisions amid fairness concerns [8], the demand information sharing strategy [9], and retailer procurement and promotion strategies [10].

(2) Coordination problems under risk aversion preference. Adhikari *et al*. [11] studied the design of a five-level textile SC coordination mechanism when there are uncertain risks of supply and demand. Liu *et al*. [12] solved the coordination problem based on option contracts and different power structures. Fan *et al*. [13] analyzed the effectiveness of the option contract coordination between bilateral participants with risk-averse. Niu *et al*. [14] discussed the SC coordination of risk-averse consumers both with and without blockchain quality information. Other studies have examined issues such as the inherent law of the buyback contract coordinate SC in the context of asymmetric production cost information and a risk-averse retailer [15], and the SC channel coordination strategy when consumers have low carbon preference and retailer have risk aversion preference [16].

Most previous studies have analyzed the impact of risk aversion preference on decision-making and coordination in SC based on the risk aversion preference of either demand uncertainty, capacity uncertainty, or quality uncertainty [17]. However, none of these investigations examined situations involving participants with risk aversion preference for random market prices, nor did they consider the existence of different power structures between the SC participants. With reference to the existing literature and real life cases, we addressed this gap by further considering uncertainty risk pertaining to product retail prices, wherein the retailer adopts a risk aversion preference for random retail prices. Meanwhile, referring to literature [18], we used mean-variance to characterize the retail price uncertainty risk. To study how both the retail price uncertainty risk and retailer's retail price risk aversion preference impacted decision-making among SC participants, we considered three different power structures in our SC game model, including MS, RS, and VN. We also compared and analyzed the equilibrium decision, profit, and utility under these power structure models.

2. Problem description and assumptions

2.1 Problem description

We considered a two-echelon SC system consisting of a risk-neutral manufacturer M and retailer R with a retail price risk aversion preference. The manufacturer first organize production according to the retailer's order quantity q and determine the input level of its production efforts e (e.g., technological innovation [19], equipment upgrading and labor input). Based on the above, we analyzed both the manufacturer's production effort input and retailer's order quantity decision under three different power structures, including a VN game, RS game, and MS game. Given the results, we discuss how retail price uncertainty risk and the retailer's retail price risk aversion impact SC participants' decision-making and profit (utility), with a comparison of Nash equilibrium results under all three power structures.

2.2 Model assumptions

<u>Assumption 1:</u> The additional input of production efforts e (e.g., technological innovation, equipment upgrading, and labor) will improve the quality of manufacturer' products to a certain extent, thus increasing the wholesale price w of products. Therefore, the manufacturer's wholesale price

w is positively correlated with the input level of production efforts e. The wholesale price function of the product is as follows:

$$w = w_0 + \lambda e \tag{1}$$

Here, w_0 is the wholesale price of the product without additional production efforts ($e = 0$) and λ is the production effort efficiency that affects the wholesale price. The larger the value of λ, the more obvious the effect of unit additional production efforts on the increase of the wholesale price.

Assumption 2: The input of additional production efforts e improves product quality, which will also increase the retail price p of products to a certain extent. In reference to previous research [20-22], the retail price function is as follows:

$$p = 1 - q + \beta e + \xi \tag{2}$$

Here, q is the retailer's order quantity, β is the production effort efficiency that affects the retail price, ξ is the random variable factor, $E(\xi) = 0$, and $Var(\xi) = \delta^2$ [22-23]. The larger the δ, the greater the volatility of the retail price or greater the risk of uncertainty. The production effort cost is $C(e) = e^2$ [21].

Assumption 3: Because the uncertainty of product retail prices will induce uncertainty risk in retailer, they will adopt a risk aversion preference for random retail prices (retail price risk aversion preference).

Assumption 4: To simplify the model without affecting the conclusion, the manufacturer's unit product production cost is $c = 0$.

3. SC models under different power structures

3.1 VN game model

In the VN game model, manufacturer and retailer have equivalent power. All carry out non-cooperative games with the goal of maximizing their expected profit (utility). At this point, the profits of the risk-neutral manufacturer $\Pi_M^V(e)$ and retailer $\Pi_R^V(q)$ are respectively as follows:

$$\Pi_M^V(e) = (w_0 + \lambda e)q - e^2 \tag{3}$$

$$\Pi_R^V(q) = (1 - q + \beta e + \xi - w_0 - \lambda e)q \tag{4}$$

Referring to both Xie *et al.* and Chiu and Choi's construction method for expected utility function in the case of SC participants with demand risk aversion preference [24-25], we constructed the expected utility function of retailer with retail price risk aversion preference, expressed as follows:

$$U_R^V(q) = E[\Pi_R^V(q)] - \frac{1}{2}\eta Var[\Pi_R^V(q)] = (1 - q + \beta e + \xi - w_0 - \lambda e)q - \frac{1}{2}\eta q^2\delta^2 \tag{5}$$

Here, η is the retailer's retail price risk aversion coefficient. The larger the value of η, the greater the retailer's risk aversion to random retail prices.

The first-order partial derivatives of Π_M^V and U_R^V with respect to e and q are as follows:

$$\begin{cases} \dfrac{\partial \Pi_M^V}{\partial e} = \lambda q - 2e = 0 \\ \dfrac{\partial U_R^V}{\partial q} = 1 + \beta e - \lambda e - w_0 - 2q - \eta\delta^2 q = 0 \end{cases} \tag{6}$$

Because $\frac{\partial^2 \Pi_M^V}{\partial e^2} = -2 < 0$ and $\frac{\partial^2 U_R^V}{\partial q^2} = -2 - \eta\delta^2 < 0$, the simultaneous solution (6) can obtain the manufacturer's unique optimal production effort input level e^{V*} and retailer's unique optimal order quantity q^{V*}, as follows:

$$\begin{cases} e^{V*} = \dfrac{\lambda(1-w_0)}{4+2\eta\delta^2-\lambda\beta+\lambda^2} \\ q^{V*} = \dfrac{2(1-w_0)}{4+2\eta\delta^2-\lambda\beta+\lambda^2} \end{cases} \tag{7}$$

Bringing e^{V*} and q^{V*} into Eqs. 3 and 5, respectively, the optimal profit of the manufacturer Π_M^{V*} and optimal expected utility of the retailer U_R^{V*} can be obtained as follows:

$$\begin{cases} \Pi_M^{V*} = \dfrac{(1-w_0)[\lambda^2+w_0(8+4\eta\delta^2-2\lambda\beta+\lambda^2)]}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2} \\ U_R^{V*} = \dfrac{2(1-w_0)^2(2+\eta\delta^2)}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2} \end{cases} \tag{8}$$

The first-order partial derivatives of the optimal decision and profit (utility) of the manufacturer and retailer with respect to η and δ are as follows:

$$\begin{cases} \dfrac{\partial e^{V*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial e^{V*}}{\partial \delta} = \dfrac{-2\lambda\delta^2(1-w_0)}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2} < 0 \\ \dfrac{\partial q^{V*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial q^{V*}}{\partial \delta} = \dfrac{-4\delta^2(1-w_0)}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2} < 0 \\ \dfrac{\partial \Pi_M^{V*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial \Pi_M^{V*}}{\partial \delta} = \dfrac{-4\delta^2(1-w_0)[\lambda^2+w_0(4+2\eta\delta^2-\lambda\beta)]}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^3} \\ \qquad < \dfrac{-4w_0\delta^2(1-w_0)(4+2\eta\delta^2-\lambda\beta+\lambda^2)}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^3} < 0 \\ \dfrac{\partial U_R^{V*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial U_R^{V*}}{\partial \delta} = \dfrac{-2\delta^2(1-w_0)^2(4+2\eta\delta^2+\lambda\beta-\lambda^2)}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^3} < 0 \end{cases} \tag{9}$$

Proposition 1: e^{V*}, q^{V*}, Π_M^{V*}, and U_R^{V*} are decreasing functions of η and δ.

In the VN game model, Proposition 1 shows that the manufacturer's profit and retailer's expected utility decrease with increases in the retail price uncertainty risk degree δ and retailer's retail price risk aversion degree η, thus reducing the manufacturer's production effort input and retailer's enthusiasm for ordering.

3.2 RS game model

In the RS game SC, the retailer is the leader and therefore has the priority to determine its order quantity q. The manufacturer then determines the input level of its production effort e based on q.

Similar to the conditions described in Section 3.1, the expected utility function of risk-neutral manufacturer's profit $\Pi_M^R(e)$ and retail price risk-aversion preference retailer $U_R^R(q)$ can be expressed as follows:

$$\begin{cases} \Pi_M^R(e) = (w_0+\lambda e)q - e^2 \\ U_R^R(q) = (1-q+\beta e-w_0-\lambda e)q - \dfrac{1}{2}\eta q^2\delta^2 \end{cases} \tag{10}$$

From Eq. 6, the manufacturer's optimal production effort e^{R*} satisfies $e^{R*} = \frac{\lambda q}{2}$. Substitute e^{R*} into Eq. 10, as follows:

$$U_R^R(q) = \frac{q[2(1-w_0)-q(2+\eta\delta^2-\lambda\beta+\lambda^2)]}{2} \tag{11}$$

The first and second partial derivatives of U_R^R with respect to q are as follows:

$$\begin{cases} \dfrac{\partial U_R^R}{\partial q} = 1 - w_0 - q(2 + \eta\delta^2 - \lambda\beta + \lambda^2) = 0 \\ \dfrac{\partial^2 U_R^R}{\partial q^2} = -(2 + \eta\delta^2 - \lambda\beta + \lambda^2) \end{cases} \tag{12}$$

When $2 + \eta\delta^2 - \lambda\beta + \lambda^2 > 0$, then $\frac{\partial^2 U_R^R}{\partial q^2} < 0$. The solution to (12) can reveal the only optimal order quantity $q^{R*} = \frac{1-w_0}{2+\eta\delta^2-\lambda\beta+\lambda^2}$.

Substituting q^{R*} into the above equation, we can obtain the retailer's optimal expected utility U_R^{R*}, manufacturer's optimal profit Π_M^{R*}, and production effort input e^{R*}, as follows:

$$\begin{cases} U_R^{R*} = \dfrac{(1-w_0)^2}{2(2 + \eta\delta^2 - \lambda\beta + \lambda^2)} \\ \Pi_M^{R*} = \dfrac{\left[(1-w_0)[\lambda^2 + w_0(8 + 4\eta\delta^2 - 4\lambda\beta + 3\lambda^2)]\right]}{4(2 + \eta\delta^2 - \lambda\beta + \lambda^2)^2} \\ e^{R*} = \dfrac{\lambda(1-w_0)}{2(2 + \eta\delta^2 - \lambda\beta + \lambda^2)} \end{cases} \tag{13}$$

The first-order partial derivatives of e^{R*}, q^{R*}, U_R^{R*}, and Π_M^{R*} with respect to η and δ are as follows:

$$\begin{cases} \dfrac{\partial e^{R*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial e^{R*}}{\partial \delta} = \dfrac{-\lambda\delta^2(1-w_0)}{2(2 + 2\eta\delta^2 - \lambda\beta + \lambda^2)^2} < 0 \\ \dfrac{\partial q^{R*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial q^{R*}}{\partial \delta} = \dfrac{-\delta^2(1-w_0)}{(2 + 2\eta\delta^2 - \lambda\beta + \lambda^2)^2} < 0 \\ \dfrac{\partial U_R^{R*}}{\partial \eta} = \dfrac{\delta}{\eta}\dfrac{\partial U_R^{R*}}{\partial \delta} = \dfrac{-\delta^2(1-w_0)^2}{2(2 + 2\eta\delta^2 - \lambda\beta + \lambda^2)^2} < 0 \\ \dfrac{\partial \Pi_M^{R*}}{\partial \eta} = \dfrac{\delta}{\eta}\dfrac{\partial \Pi_M^{R*}}{\partial \delta} = \dfrac{-\delta^2(1-w_0)[\lambda^2 + w_0(4 + 2\eta\delta^2 - 2\lambda\beta + \lambda^2)]}{2(2 + \eta\delta^2 - \lambda\beta + \lambda^2)^3} \\ \quad < \dfrac{-2w_0\delta^2(1-w_0)(2 + 2\eta\delta^2 - \lambda\beta + \lambda^2)}{2(2 + \eta\delta^2 - \lambda\beta + \lambda^2)^3} < 0 \end{cases} \tag{14}$$

Proposition 2: e^{R*}, q^{R*}, U_R^{R*}, and Π_M^{R*} are all decreasing functions for η and δ.

In the RS game model, Proposition 2 shows that the degree of uncertainty risk of the retail price and the degree of risk aversion of the retailer's retail price will not only weaken the manufacturer's production effort input, but will also weaken the enthusiasm retailer has for placing orders. This arrangement simultaneously harms the interests of manufacturer and retailer.

3.3 MS game model

If the manufacturer is the Stackelberg game leader of the SC, then the order of the SC is: the manufacturer first determines the input level of its production efforts e, then the retailer determines its order quantity q according to the manufacturer's decision. Similar to the conditions described in Section 3.1, the expected utility function of risk-neutral manufacturer's profit $\Pi_M^M(e)$ and retail price risk-aversion preference retailer $U_R^M(q)$ is expressed as follows:

$$\begin{cases} \Pi_M^M(e) = (w_0 + \lambda e)q - e^2 \\ U_R^M(q) = (1 - q + \beta e - w_0 - \lambda e)q - \dfrac{1}{2}\eta q^2\delta^2 \end{cases} \tag{15}$$

Because $\frac{\partial^2 U_R^M}{\partial q^2} = -2 - \eta\delta^2 < 0$, the solution to $\frac{\partial U_R^M}{\partial q} = 0$ can reveal the retailer's only optimal order quantity $q^{M*} = \frac{1-w_0+\beta e-\lambda e}{2+\eta\delta^2}$.

Substitute q^{M*} into Eq. 15, as follows:

$$\Pi_M^M(e) = \frac{(w_0 + \lambda e)[1 - w_0 + e(\beta - \lambda)]}{2 + \eta\delta^2} - e^2 \tag{16}$$

The first and second partial derivatives of Π_M^M with respect to e are as follows:

$$\begin{cases} \dfrac{\partial \Pi_M^M}{\partial e} = \dfrac{w_0(\beta - 2\lambda) + \lambda - 2e(2 + \eta\delta^2 - \lambda\beta + \lambda^2)}{2 + \eta\delta^2} \\ \dfrac{\partial^2 \Pi_M^M}{\partial e^2} = \dfrac{-2(2 + \eta\delta^2 - \lambda\beta + \lambda^2)}{2 + \eta\delta^2} \end{cases} \tag{17}$$

From Eq. 17, when $2 + \eta\delta^2 - \lambda\beta + \lambda^2 > 0$, we have $\frac{\partial^2 \Pi_M^M}{\partial e^2} < 0$. We then let $\frac{\partial \Pi_M^M}{\partial e} = 0$, such that the optimal production effort input of the manufacturer is $e^{M*} = \frac{w_0\beta + \lambda - 2\lambda w_0}{4 + 2\eta\delta^2 - 2\lambda\beta + 2\lambda^2}$.

Therefore, we can obtain the optimal profit of the manufacturer Π_M^{M*}, the optimal expected utility of the retailer U_R^{M*}, and the order quantity q^{M*} as follows:

$$\begin{cases} \Pi_M^{M*} = \dfrac{\lambda^2 + w_0(8 + 4\eta\delta^2 - 2\lambda\beta) - {w_0}^2(8 + 4\eta\delta^2 - \beta^2)}{2(2 + \eta\delta^2)(4 + 2\eta\delta^2 - 2\lambda\beta + 2\lambda^2)} \\ U_R^{M*} = \dfrac{[4 + 2\eta\delta^2 - \lambda\beta + \lambda^2 - w_0(4 + 2\eta\delta^2 - \beta^2 + \lambda\beta)]^2}{2(2 + \eta\delta^2)(4 + 2\eta\delta^2 - 2\lambda\beta + 2\lambda^2)^2} \\ q^{M*} = \dfrac{4 + 2\eta\delta^2 - w_0(4 + 2\eta\delta^2 - \beta^2) - \beta\lambda(1 + w_0) + \lambda^2}{(2 + \eta\delta^2)(4 + 2\eta\delta^2 - 2\lambda\beta + 2\lambda^2)} \end{cases} \tag{18}$$

The first-order partial derivatives of e^{M*}, q^{M*}, U_R^{M*}, and Π_M^{M*} with respect to η and δ are as follows:

$$\begin{cases} \dfrac{\partial e^{M*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial e^{M*}}{\partial \delta} = \dfrac{-\delta^2(w_0\beta + \lambda - 2\lambda w_0)}{2(2 + \eta\delta^2 - \lambda\beta + \lambda^2)^2} < 0 \\ \dfrac{\partial q^{M*}}{\partial \eta} = \dfrac{\delta}{\eta}\dfrac{\partial q^{M*}}{\partial \delta} = \dfrac{\delta^2[2(1 - w_0)(2A_3 - \eta^2\delta^4) - A_1(2 + A_3 + 2\eta\delta^2)]}{2(2 + \eta\delta^2)^2(A_3 + \eta\delta^2)^2} \\ \qquad < -\dfrac{\delta^2(\lambda - \beta)^2(4 + 2\eta\delta^2 - \lambda\beta + \lambda^2)}{2(2 + \eta\delta^2)^2(A_3 + \eta\delta^2)^2} < 0 \\ \dfrac{\partial U_R^{M*}}{\partial \eta} = \dfrac{\delta}{\eta}\dfrac{\partial U_R^{M*}}{\partial \delta} \\ = \dfrac{\delta^2[2\eta\delta^2(1 - w_0) - A_1]\{A_1(4 + A_3 + 3\eta\delta^2) + 2(1 - w_0)[A_3(4 + \eta\delta^2) - \eta^2\delta^4]\}}{8(2 + \eta\delta^2)^2(A_3 + \eta\delta^2)^3} \\ \qquad < -\dfrac{\delta^2(\lambda - \beta)^4(6 + 3\eta\delta^2 - \lambda\beta + \lambda^2)}{8(2 + \eta\delta^2)^2(A_3 + \eta\delta^2)^3} < 0 \\ \dfrac{\partial \Pi_M^{M*}}{\partial \eta} = \dfrac{\delta}{\eta}\dfrac{\partial \Pi_M^{M*}}{\partial \delta} = \dfrac{\delta^2[4w_0(1 - w_0)(2A_3 - \eta^2\delta^4) - A_2(2 + A_3 + 2\eta\delta^2)]}{4(2 + \eta\delta^2)^2(A_3 + \eta\delta^2)^2} \\ \qquad < -\dfrac{\delta^2(\lambda - \beta)^2(4 + 2\eta\delta^2 - \lambda\beta + \lambda^2)}{4(2 + \eta\delta^2)^2(A_3 + \eta\delta^2)^2} < 0 \end{cases} \tag{19}$$

Here, $A_1 = 4 - \lambda\beta(1 + w_0) + \lambda^2 - w_0(4 - \beta^2)$, $A_2 = \lambda^2 + w_0(8 - 2\beta\lambda) - {w_0}^2(8 - \beta^2)$, and $A_3 = 2 - \lambda\beta + \lambda^2$.

<u>Proposition 3:</u> e^{M*}, q^{M*}, U_R^{M*}, and Π_M^{M*} are all decreasing functions pertaining to η and δ.

From Proposition 3, it can be concluded that both the degree of uncertainty risk of retail price δ and degree of risk aversion of the retailer's retail price η will negatively impact the income of manufacturer and retailer in the MS game model. In turn, this will promote the manufacturer's production effort input and the retailer's order quantity reduction.

Table 1 The effects of η and δ on the manufacturer's production effort input and retailer's order quantity

δ	η	e^{V*}	e^{R*}	e^{M*}	q^{V*}	q^{R*}	q^{M*}
0.2	0.2	0.232	0.347	0.496	0.464	0.694	0.596
	0.4	0.231	0.344	0.492	0.462	0.689	0.591
	0.8	0.228	0.339	0.484	0.457	0.678	0.583
0.4	0.2	0.228	0.339	0.484	0.457	0.678	0.583
	0.4	0.224	0.329	0.470	0.448	0.658	0.567
	0.8	0.215	0.310	0.443	0.430	0.621	0.537
0.8	0.2	0.215	0.310	0.443	0.430	0.621	0.537
	0.4	0.199	0.279	0.399	0.399	0.557	0.487
	0.8	0.174	0.231	0.331	0.348	0.463	0.410

Table 2 The effects of η and δ on the manufacturer's profit and retailer's expected utility

δ	η	U_R^{V*}	U_R^{R*}	U_R^{M*}	Π_M^{V*}	Π_M^{R*}	Π_M^{M*}
0.2	0.2	0.216	0.243	0.356	0.193	0.329	0.228
	0.4	0.215	0.241	0.352	0.192	0.325	0.226
	0.8	0.212	0.237	0.345	0.189	0.319	0.223
0.4	0.2	0.212	0.237	0.345	0.189	0.319	0.223
	0.4	0.207	0.230	0.332	0.184	0.306	0.216
	0.8	0.197	0.217	0.307	0.175	0.282	0.203
0.8	0.2	0.197	0.217	0.307	0.175	0.282	0.203
	0.4	0.179	0.195	0.267	0.159	0.245	0.181
	0.8	0.152	0.162	0.211	0.135	0.192	0.149

To further validate our conclusions, we conducted an analysis using numerical examples. Without loss of generality, take the parameters $w_0 = 0.3$, $\lambda = 1.0$ and $\beta = 2.0$, which result in the arrangements shown in Tables 1 and 2.

4. Comparing the models

In the previous section, we explained how we solved the optimal decision, profit, and utility of SC participants under different power structure models. As described in this section, we then compared and analyzed the Nash equilibrium results in three cases.

$$\begin{cases} e^{R*} - e^{V*} = \dfrac{\lambda^2(1-w_0)(\beta-\lambda)}{2(2+\eta\delta^2-\lambda\beta+\lambda^2)(4+2\eta\delta^2-\lambda\beta+\lambda^2)} \\ e^{M*} - e^{R*} = \dfrac{w_0(\beta-\lambda)}{4+2\eta\delta^2-2\lambda\beta+2\lambda^2} \end{cases} \tag{20}$$

<u>Proposition 4:</u>

- If $\beta < \lambda$, then $e^{R*} < e^{V*} < e^{M*}$
- If $\beta > \lambda$, then $e^{V*} < e^{R*} < e^{M*}$

From Proposition 4, we can make two conclusions. If the efficiency of the production effort affecting wholesale price λ is greater than that affecting retail price β, then the manufacturer's production effort input level is the largest under the VN game model, followed by the RS game model and MS game model. To the contrary, if λ is less than β, then the manufacturer's production effort input level is the largest under the MS game model, followed by the RS game model and VN game model (Fig. 1).

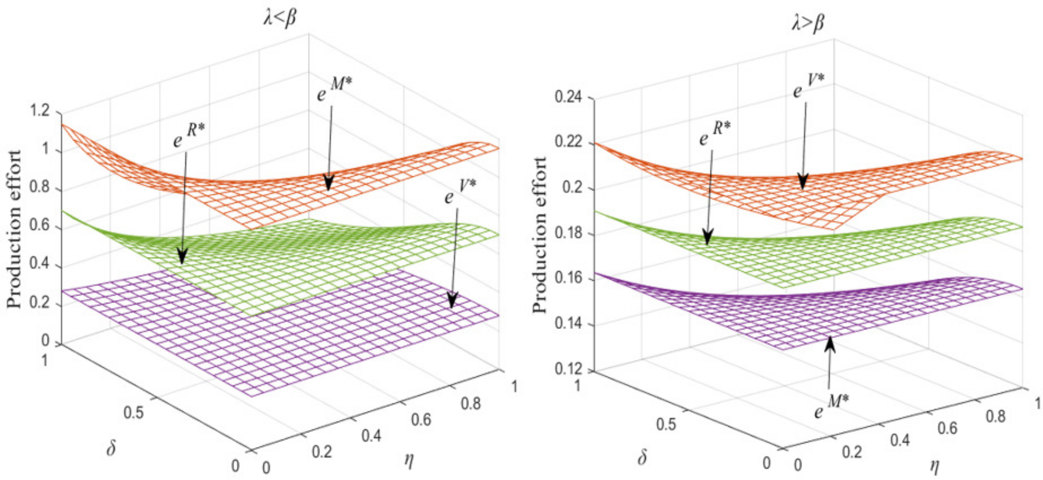

Fig. 1 The effects of δ and η on the manufacturer's production effort

$$\begin{cases} q^{R*} - q^{V*} = \dfrac{\lambda(1-w_0)(\beta-\lambda)}{(2+\eta\delta^2-\lambda\beta+\lambda^2)(4+2\eta\delta^2-\lambda\beta+\lambda^2)} \\ q^{M*} - q^{R*} = \dfrac{(w_0\beta-\lambda)(\beta-\lambda)}{2(2+\eta\delta^2)(4+2\eta\delta^2-2\lambda\beta+2\lambda^2)} \\ q^{M*} - q^{V*} = \dfrac{(\beta-\lambda)^2[\lambda^2+w_0(4+2\eta\delta^2-\lambda\beta)]}{2(2+\eta\delta^2)(2+\eta\delta^2-\lambda\beta+\lambda^2)(4+2\eta\delta^2-\lambda\beta+\lambda^2)} \\ \qquad > \dfrac{w_0(\beta-\lambda)^2}{2(2+\eta\delta^2)(2+\eta\delta^2-\lambda\beta+\lambda^2)} > 0 \end{cases} \tag{21}$$

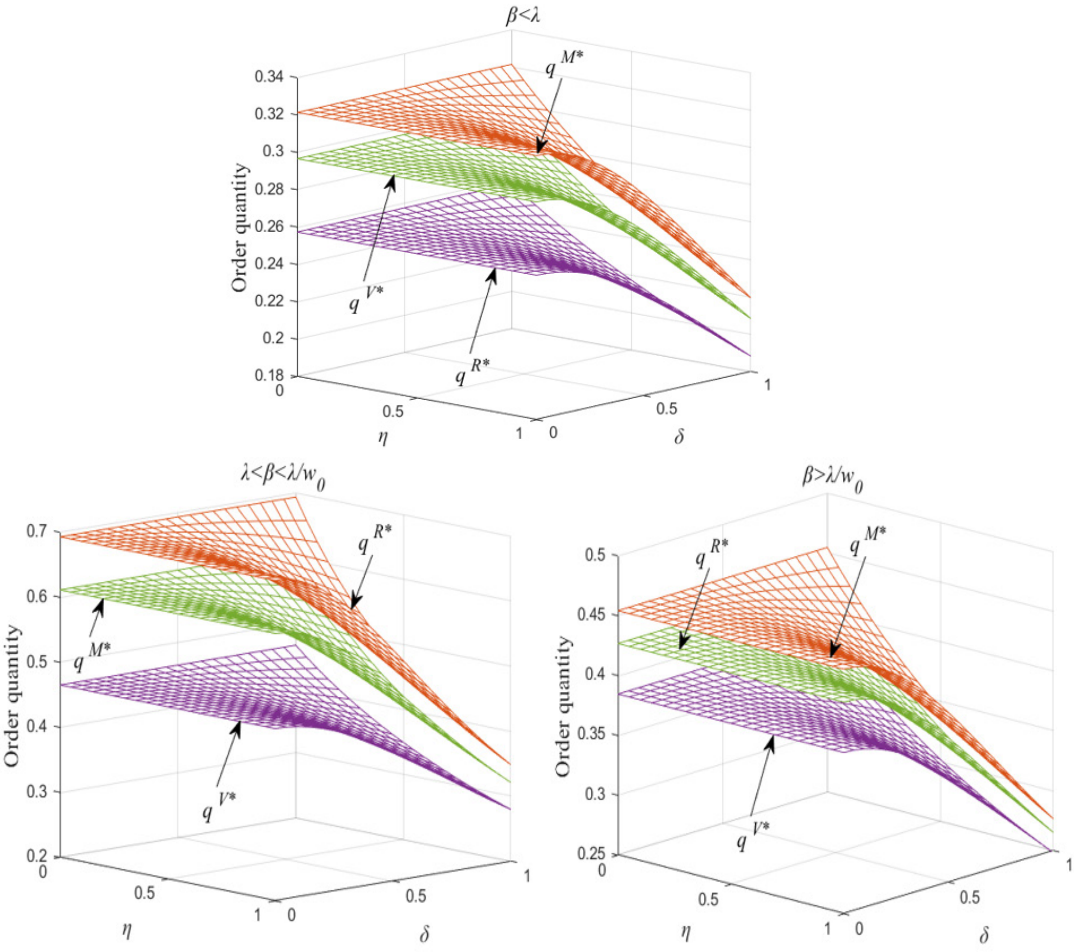

Fig. 2 The effects of δ and η on the retailer's order quantity

Proposition 5 is obtained through Eq. 21.

Proposition 5:

- If $\beta < \lambda$, then $q^{R*} < q^{V*} < q^{M*}$
- If $\lambda < \beta < \lambda/w_0$, then $q^{V*} < q^{M*} < q^{R*}$
- If $\beta > \lambda/w_0$, then $q^{V*} < q^{R*} < q^{M*}$

From Proposition 5, we can make three conclusions. If the efficiency of the production effort affecting retail price β is small, then the retailer's order quantity is largest under the MS game model, followed by the VN game model and RS game model. If β is medium, then the retailer's order quantity is largest under the RS game model, followed by the MS game model and VN game model. If β is relatively large, then the retailer's order quantity is largest under the MS game model, followed by the RS game model and VN game model (Fig. 2).

$$\begin{cases} U_R^{R*} - U_R^{V*} = \dfrac{\lambda^2(1-w_0)^2(\beta-\lambda)^2}{2(2+\eta\delta^2-\lambda\beta+\lambda^2)(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2} > 0 \\ U_R^{M*} - U_R^{R*} = \dfrac{[\lambda^2+w_0(8+4\eta\delta^2-2\lambda\beta)]-{w_0}^2(8+4\eta\delta^2-\beta^2)(\beta-\lambda)^2}{2(2+\eta\delta^2)(4+2\eta\delta^2-2\lambda\beta+2\lambda^2)^2} > 0 \end{cases} \tag{22}$$

Proposition 6: $U_R^{M*} > U_R^{R*} > U_R^{V*}$.

According to Proposition 6, the retailer always obtains the maximum expected utility under the MS game model, but obtains the minimum expected utility under the VN game model (Fig. 3).

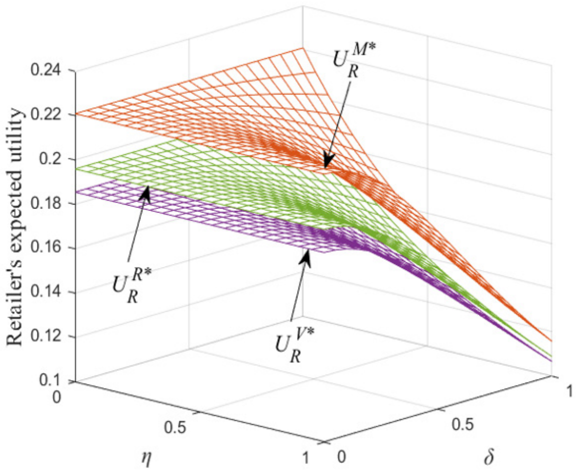

Fig. 3 The effects of δ and η on the retailer's expected utility

$$\begin{cases} \Pi_M^{M*} - \Pi_M^{V*} = \dfrac{(\beta-\lambda)^2[\lambda^2+w_0(4+2\eta\delta^2-\lambda\beta)]^2}{2(2+\eta\delta^2)(4+2\eta\delta^2-2\lambda\beta+2\lambda^2)(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2} > 0 \\ \Pi_M^{M*} - \Pi_M^{R*} = \dfrac{H_1(\beta,\lambda,w_0,\eta,\delta)}{2(2+\eta\delta^2)(4+2\eta\delta^2-2\lambda\beta+2\lambda^2)} \\ \Pi_M^{R*} - \Pi_M^{V*} = \dfrac{\lambda(1-w_0)H_2(\beta,\lambda,w_0,\eta,\delta)}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2(4+2\eta\delta^2-2\lambda\beta+2\lambda^2)^2} \end{cases} \tag{23}$$

$$\begin{cases} H_1(\beta,\lambda,w_0,\eta,\delta) = (\beta-\lambda)\{\beta{w_0}^2(2+\eta\delta^2) - \lambda w_0[4-2w_0 \\ \quad +w_0\beta^2+\eta\delta^2(2-w_0)] + 2\beta\lambda^2 w_0 - \lambda^3\} \\ H_2(\beta,\lambda,w_0,\eta,\delta) = (\beta-\lambda)\{8w_0(2+\eta\delta^2)^2 - 12\beta\lambda w_0(2+\eta\delta^2) \\ +4\lambda^2[2+\eta\delta^2+w_0(4+2\eta\delta^2+\beta^2)] - \beta\lambda^3(3+5w_0) + \lambda^4(3+w_0)\} \end{cases} \tag{24}$$

Proposition 7:

- If $H_1(\beta,\lambda,w_0,\eta,\delta) > 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) < 0$, then $\Pi_M^{M*} > \Pi_M^{V*} > \Pi_M^{R*}$

- If $H_1(\beta,\lambda,w_0,\eta,\delta) > 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) > 0$, then $\Pi_M^{M*} > \Pi_M^{R*} > \Pi_M^{V*}$
- If $H_1(\beta,\lambda,w_0,\eta,\delta) < 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) > 0$, then $\Pi_M^{R*} > \Pi_M^{M*} > \Pi_M^{V*}$
- If $H_1(\beta,\lambda,w_0,\eta,\delta) < 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) < 0$, then there is no solution

Proposition 7 shows a complex situation for manufacturer's profit under the three power structures, depending on parameters $(\beta,\lambda,w_0,\eta,\delta)$. If the parameters satisfy $H_1(\beta,\lambda,w_0,\eta,\delta) > 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) < 0$, then the manufacturer obtains maximum profit under the MS game model, followed by the VN game model and RS game model. If the parameters satisfy $H_1(\beta,\lambda,w_0,\eta,\delta) > 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) > 0$, then the manufacturer also obtains maximum profit under the MS game model, this time followed by the RS game model and VN game model. If each parameter satisfies $H_1(\beta,\lambda,w_0,\eta,\delta) < 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) > 0$, then the manufacturer obtains maximum profit under the RS game model, followed by the MS game model and VN game model. However, the case of $H_1(\beta,\lambda,w_0,\eta,\delta) < 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) < 0$ does not exist. Fig. 4 illustrates these arrangements.

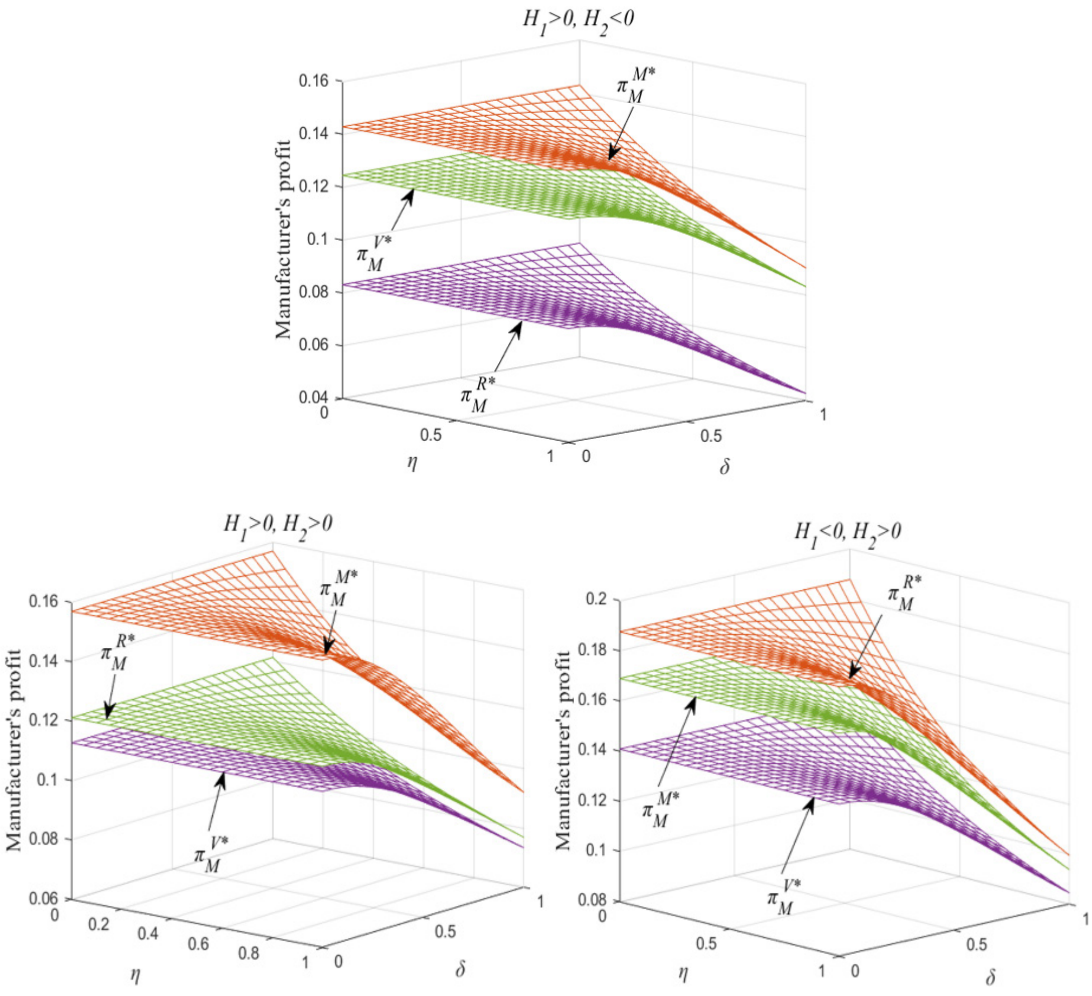

Fig. 4 The effects of δ and η on the manufacturer's profit

5. Conclusion

In a two-level SC consisting of a single manufacturer and single retailer, the product retail price is considered uncertain and affected by the manufacturer's production efforts. In this study, we used the mean-variance method to describe the uncertainty of retail prices, with a consideration of retail price risk aversion preference. Based on three different power structures, including a MS game, RS game, and VN game, we examined how the degree of both retail price uncertainty risk and retail price risk aversion impacted decision-making, profit, and utility among SC participants.

We then compared and analyzed optimal decisions, profits, and utility between these power structure models. In sum, we draw the following five conclusions:

- The uncertainty risk δ of the retail price and the retailer's retail price risk aversion η will not only reduce the manufacturer's production effort input and retailer's enthusiasm for ordering, but will also adversely affect the manufacturer's profit and retailer's expected utility.
- If the efficiency of the production effort affecting the wholesale price λ is less than the efficiency of the production effort affecting the retail price β(that is, $\lambda < \beta$), then the manufacturer's production effort input e^{M*} is largest under the MS game model, while the production effort input is smallest under the VN game model(that is, $e^{V*} < e^{R*} < e^{M*}$) . In the reverse arrangement $\lambda > \beta$, the conclusion is completely opposite, (that is, $e^{M*} < e^{R*} < e^{V*}$).
- If the efficiency β of the production effort affecting the retail price is small (that is $\lambda > \beta$), then the retailer's order quantity is largest under the MS game model and smallest under the RS game model (that is, $q^{R*} < q^{V*} < q^{M*}$). If the β in general (that is, $\lambda < \beta < \lambda/w_0$), then the retailer's order quantity is largest under the MS game model and smallest under the VN game model (that is, $q^{V*} < q^{M*} < q^{R*}$). If the β is large (that is, $\beta > \lambda/w_0$), then the retailer's order quantity is largest under the MS game model and smallest under the VN game model (that is, $q^{V*} < q^{R*} < q^{M*}$).
- The retailer always obtains the maximum expected utility under the MS game model, but obtains the minimum expected utility under the VN game model (that is, $U_R^{M*} > U_R^{R*} > U_R^{V*}$).
- Under the three power structure models, optimal manufacturer profits depend on the parameter $(\beta, \lambda, w_0, \eta, \delta)$.

This paper solves how the SC enterprises should make the most favorable decisions for themselves when there are retail price risk and the retailer has retail price risk aversion preference under different power structure situations, so as to provide theoretical guidance for enterprises to make decisions. In the future, we can continue to consider the presence of multiple manufacturers, multiple retailers and multi-supply chains.

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