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HEDGING STRATEGIES OF SUPPLY CHAIN UNDER RISK AVERSION

Abstract: *This study investigates the effects of risk aversion factors and opportunity cost on the hedging decisions of supply chain members. We develop a two-stage model consisting of a risk-averse manufacturer and an equally risk-averse retailer. We consider four strategies from the perspective of the supply chain as a whole, where neither side hedges (NN), only the supplier hedges (HN), only the manufacturer hedges (NH), and both sides hedge (HH). Then, we applied the mean-variance model and solved and compared the four strategies using the inverse solving method. The results show that the hedging strategies among the supply chain members are consistent. When both parties have high-risk aversion and opportunity cost, both parties choose to hedge the risk; when both parties have a low-risk aversion, the party with lower opportunity cost should choose to hedge.*

Keywords: *supply chain; risk aversion; hedging; mean-variance.*

JEL Classification: C51, C61, C72, M11

DOI: 10.24818/18423264/57.1.23.05

1. Introduction

With the development of economic globalisation, the cooperation between enterprises in different countries is getting closer and closer. As a result, it also aggravates the impact of price volatility on all parties. The slow growth of the world economy under the impact of the epidemic (Baumeister and Guérin, 2021), and the currency depreciation overlaid with the supply-demand gap, have pushed up the prices of global industrial raw materials priced in US dollars (Jiménez-Rodríguez and Morales-Zumaquero, 2022), and intensified the risk of inflation in the world economy (Ciccarelli and García, 2021), which has posed a severe test to the smooth operation of enterprises. As a result, there is a growing need for companies to mitigate the risk of price fluctuations through hedging (Cummins et al., 2001). For example, Coca-Cola participates in annual hedging activities in the futures market for various raw materials (Korolyova, 2021). Hedging not only hedges the risks associated with rising spot prices but also improves the efficiency of a company's use of capital. But to a certain extent, it also loses the benefits that can be gained when the spot price falls, i.e., opportunity costs. Companies face different situations in the hedging process, and the next issue to be studied is how to reasonably hedge the risk according to their situation.

Our study considers a two-tier supply chain consisting of a risk-averse supplier and a risk-averse manufacturer, both of whom are eligible to choose to hedge. The supplier purchases raw materials (e.g., wheat) to process into semi-finished products (e.g., flour) and provides them to the manufacturer, who out-processes the semi-finished products into finished products. Do we mainly examine how the risk aversion factor and opportunity cost affect the optimal profit? Should suppliers and manufacturers choose to hedge? To answer these questions, we will construct a model and perform an arithmetic analysis.

The rest of the paper is organised as follows: Section 2 summarises the most relevant literature. In section 3, the problem description, and mathematical formulation are provided. In Section 4, we solve and analyse the model. We study the optimal hedging strategy for suppliers and manufacturers in Section 5, while in Section 6 we select the relevant values for the arithmetic analysis of the results. Finally, Section 7 concludes with our findings, management insights, and future research ideas.

2. Literature review

Uncertainty has been the focus of supply chain research due to the presence of various uncontrollable factors in production and markets. Zimmer (2002) analysed the different decision problems of suppliers and retailers under output uncertainty and market demand certainty. Ma et al. (2016) studied the ordering decisions of loss-averse newsboys under supply and demand uncertainty. The negative impact of the supply risk on the utility was demonstrated to be greater than that of the demand risk. Jian et al. (2015) proposed a novel statistical forecasting method based on a dynamic relationship identification algorithm (SF-DRIA) according to the uncertainty of demand. Manoj Kulchania and Thomas (2017) found that companies facing higher expected disruption costs typically save more cash from the capital released by supply chain management innovations. Gao (2015) studied the impact of interperiod and decentralisation on disruption risk in a supply chain managing sales losses and fixed transportation costs.

Hedging has been introduced into supply chains to cope with uncertainty in various segments and to reduce the impact of price volatility on the profits of supply chain members. Bolandifar and Chen. (2020) investigate optimal hedging strategies for risk-neutral firms in a supply chain environment. Index-based price contracts were found to be a means of linking the profits of processors and retailers. Caldentey and Haugh (2009) found that producers prefer flexible contracts over hedging. Kang et al. (2018) find that supplier hedging helps to improve the perceptibility of future customer relationships and mitigate potential negative spillover effects along the supply chain. Kouvelis et al. (2019) studied cash flow risk in hedging supply chains. The results of Armeanu et al. (2013) showed that both the optimal hedging ratio and the hedging effectiveness increased with the increase in hedging duration. Models with cointegrating relationships between spot and future prices perform better than simple OLS regressions. Turcic et al.(2015) explored the advantages of hedging stochastic input costs in a decentralised, risk-neutral supply chain. It was found that, to some extent, hedging can ensure the continuity of supply. Gao et al. (2019) found that the hedging ratio is positively associated with consumer preference for green products.

Most of the above studies consider the risk preferences of supply chain members as risk neutral, but with the increasing competition, today's firms are increasingly risk-averse in their attitude toward risk. This also provides new ideas for the research of experts and scholars. Yang et al. (2021) found that risk-averse attitudes of supply chain members play an important role in determining the financing equilibrium. Mauro et al. (2020) investigated the effect of individual risk aversion on replenishment decisions in a multilevel supply chain and explored whether this effect is influenced by empirical learning. Oliveira et al. (2021) used risk-averse producers and retailers to analyse the power supply chain procurement problem with the interaction between futures and spot prices. Bai et al. (2020) studied the effect of risk aversion on system coordination under a two-part tariff contract under a carbon tax policy. Raza and Govindaluri (2019) developed a dual-channel supply chain coordination model to investigate the effects of risk aversion, demand leakage, and market uncertainty on supply chain coordination performance. Li et al. (2018) found that hedging effectively reduced the manufacturer's commodity price risk to retailers and maintained the benefits of flexible price contracts. Zhao et al. (2010) used a cooperative game approach to study the coordination of a manufacturer-retailer supply chain using options contracts. Scenarios in which options contracts are chosen based on individual supply chain members' risk preferences and bargaining power are also discussed.

Most of the above studies consider one decision maker as risk-averse and others as risk-neutral by default. However, in today's business environment, competition is increasingly fierce, the general environment is volatile, and every aspect of the process, from output to sales, faces a variety of uncertainties. For small and medium-sized enterprises, poor risk resistance. Therefore, in the next study, two decision-makers, a supplier and a manufacturer, are considered risk-averse, and the manufacturer has pricing power in the final product market. From the perspective of the supply chain as a whole, four strategies are considered: no hedging by both parties, hedging by the supplier only, hedging by the manufacturer only, and hedging by both parties, and the mean-variance model is used to explore the effects of opportunity costs and the degree of risk aversion of supply chain members on the hedging strategy.

3. Mathematical modeling

In our model, the supplier provides the manufacturer with processing materials and needs to obtain an equal amount of raw materials from the market for production, and the manufacturing processes and puts the product on the market. We assume that both the supplier and the manufacturer can produce one unit of finished product from one unit of raw material. In the production process, to cope with the risk brought to both parties by the fluctuation of raw material prices, suppliers and manufacturers can choose to use hedging to hedge the risk to some extent. According to their different choices for hedging, there are four different scenarios: (1) HH scenario: both suppliers and manufacturers choose hedging strategy; (2) HN scenario: only suppliers choose to hedge; (3) NH scenario: only manufacturers choose to hedge; (4) NN scenario: neither suppliers nor manufacturers choose to hedge. Whether to hedge or not is a matter of decision for the supplier and the manufacturer.

The demand function is formulated as follows:

$$q = a - bp \tag{1}$$

The above equation, a represents the market potential and, $a > 0$, b represents the price elasticity, p represents the product price.

For suppliers and manufacturers, if they do not hedge, the cost $c_{i0}(i = s, m)$ is flexible and varies with the movement of the spot price. We divide it into two parts. A part of the supplier's cost is the spot price c_s of raw materials at $t = 0$ and a part of it is ζ that changes later with the market price of raw materials; a part of the manufacturer's cost is the spot price c_m of processed materials at $t = 0$ and a part of it is ε that changes later with the market price of processed materials, then the supplier's cost is described as $c_{s0} = c_s + \zeta$ and the manufacturer's cost is described as $c_{m0} = c_m + \varepsilon$. where ζ obeys a normal distribution $(0, \sigma_s^2)$ and ε obeys a normal distribution $(0, \sigma_m^2)$. If a hedge is chosen, its raw material cost is fixed at the opening spot price c_i, but this move will certainly incur an opportunity cost, which will be assumed to be Δc_i. The cost of both is described by $c_{i0} = c_i + \Delta c_i$. The wholesale price is denoted by w.

The profit functions of the supplier and the manufacturer are formulated, respectively:

$$\pi_s = (w - c_{s0})q \tag{2}$$

$$\pi_m = (p - w - c_{m0})q \tag{3}$$

In the subsequent calculations, to simplify the expressions, we let $c_{s+m} = c_s + c_m$, $\Delta c_{s+m} = \Delta c_s + \Delta c_m$.

4. Solution method for model

For supply chain members that do not hedge, their utility is described by a mean-variance model, and supply chain members that choose to hedge are described by an ordinary profit function.

4.1 The case of NN

In the case of NN, both the supplier and the manufacturer choose not to hedge, in which case the utilities of the supplier and the manufacturer are expressed as:

$$U_s^{NN} = E(\pi_s^{NN}) - \frac{\lambda_s}{2} Var(\pi_s^{NN}) \tag{4}$$

$$U_m^{NN} = E(\pi_m^{NN}) - \frac{\lambda_m}{2} Var(\pi_m^{NN}) \tag{5}$$

Proposition 1. In the case where neither the supplier nor the manufacturer hedges, the optimal solution of the wholesale price and the market price are obtained, according to the first-order condition, as:

$$w^{NN*} = \frac{a - b^2 c_m \lambda_s \sigma_s^2 + b^2 c_s \lambda_m \sigma_m^2 + b^2 c_s \lambda_s \sigma_s^2 + ab\lambda_s \sigma_s^2 - bc_m + 3bc_s}{b(2b\lambda_s \sigma_s^2 + b\lambda_m \sigma_m^2 + 4)} \tag{6}$$

$$p^{NN*} = \frac{3a + ab\lambda_m \sigma_m^2 + 2ab\lambda_s \sigma_s^2 + bc_{s+m}}{b(2b\lambda_s \sigma_s^2 + b\lambda_m \sigma_m^2 + 4)} \tag{7}$$

The optimal utility of the supplier and the manufacturer are expressed as follows

$$U_s^{NN*} = \frac{(b\lambda_s \sigma_s^2 + 2)(a - bc_{s+m})^2}{2b(2b\lambda_s \sigma_s^2 + b\lambda_m \sigma_m^2 + 4)} \tag{8}$$

$$U_m^{NN*} = \frac{(a - bc_{s+m})^2}{2b(2b\lambda_s \sigma_s^2 + b\lambda_m \sigma_m^2 + 4)} \tag{9}$$

Proposition 1 shows that the optimal wholesale price w is positively related to the supplier risk coefficient λ_s and negatively related to the manufacturer risk coefficient λ_m. The optimal market price p is positively related to both the supplier risk coefficient λ_s and the manufacturer risk coefficient λ_m. The optimal utility of both, on the other hand, decreases as the risk factor of either party increases.

4.2 The case of HN

In the HN case, only the supplier chooses to hedge. At this point, the profit function of the manufacturer and the utility function of the supplier are:

$$\pi_s^{HN} = (w - c_s - \Delta c_s)q \tag{10}$$

$$U_m^{HN} = E(\pi_m^{HN}) - \frac{\lambda_m}{2} Var(\pi_m^{HN}) \tag{11}$$

Proposition 2 In the case where the supplier chooses to hedge and the manufacturer does not hedge, the optimal solution of the wholesale price and the market price is obtained according to the first-order condition:

$$w^{HN*} = \frac{a + b^2 c_s \lambda_m \sigma_m^2 + b^2 \Delta c_s \lambda_m \sigma_m^2 - bc_m + 3bc_s + 3b\Delta c_s}{b(b\lambda_m \sigma_m^2 + 4)} \tag{12}$$

$$p^{HN*} = \frac{3a + ab\lambda_m \sigma_m^2 + bc_{s+m} + b\Delta c_s}{b(b\lambda_m \sigma_m^2 + 4)} \tag{13}$$

The supplier's profit and the manufacturer's optimal utility are described respectively：

$$\pi_s^{HN*} = \frac{(a - bc_{s+m} - b\Delta c_s)^2}{b(b\lambda_m \sigma_m^2 + 4)^2} \tag{14}$$

$$U_m^{HN*} = \frac{(a - bc_{s+m} - \Delta bc_s)^2}{2b(b\lambda_m \sigma_m^2 + 4)} \tag{15}$$

Proposition 2 suggests that in the HN case, the optimal wholesale price w is negatively related to the manufacturer's risk coefficient λ_m and positively related to the supplier's opportunity cost Δc_s. The optimal market price p is positively related to both the manufacturer's risk coefficient λ_m and the supplier's opportunity cost Δc_s. Both the supplier's profit and the manufacturer's optimal utility are negatively related to the manufacturer's risk coefficient λ_m and the supplier's opportunity cost Δc_s.

4.3 The case of NH

In the NH case, only the manufacturer chooses to hedge and the supplier does not hedge. At this point, the manufacturer's utility function and the supplier's profit function are：

$$U_s^{NH} = E(\pi_s^{NH}) - \frac{\lambda_2}{2} Var(\pi_s^{NH}) \tag{16}$$

$$\pi_m^{NH} = (p - w - c_m - \Delta c_m)q \tag{17}$$

Proposition 3 In the case where the manufacturer chooses to hedge and the supplier does not hedge, the optimal solution of the wholesale price and the market price can be obtained according to the first-order condition, i.e.

$$w^{NH*}=\frac{a-b^2c_m\lambda_s\sigma_s^2-b^2\Delta c_m\lambda_s\sigma_s^2+b^2c_s\lambda_s\sigma_s^2+ab\lambda_s\sigma_s^2-bc_m-b\Delta c_m+3bc_s}{2b(b\lambda_s\sigma_s^2+2)} \quad (18)$$

$$p^{NH*}=\frac{3a+2ab\lambda_s\sigma_s^2+bc_{s+m}+b\Delta c_m}{2b(b\lambda_s\sigma_s^2+2)} \quad (19)$$

Then the optimal utility of the supplier and the profit of the manufacturer are：

$$U_s^{NH*}=\frac{(a-bc_{s+m}-b\Delta c_m)^2}{8b(b\lambda_s\sigma_s^2+2)} \quad (20)$$

$$\pi_m^{NH*}=\frac{(a-bc_{s+m}-b\Delta c_m)^2}{4b(b\lambda_s\sigma_s^2+2)} \quad (21)$$

Observing **Proposition 3**, it is found that in the NH case, the optimal wholesale price w is positively related to the supplier risk coefficient λ_s and negatively related to the manufacturer opportunity cost Δc_m; the optimal market price p is positively related to both the supplier risk coefficient λ_s and the manufacturer opportunity cost Δc_m, and both the optimal utility of the supplier and the manufacturer profit are negatively related to the supplier risk coefficient λ_s and the manufacturer opportunity cost Δc_m.

4.4 The case of HH

In the HH case, both the manufacturer and the supplier choose to hedge, and in this case, at this time, the profit functions of the manufacturer and the supplier are：

$$\pi_s^{HH}=(w-c_s-\Delta c_s)q \quad (22)$$

$$\pi_m^{HH}=(p-w-c_m-\Delta c_m)q \quad (23)$$

Proposition 4 In the case where neither the manufacturer nor the supplier hedges, the optimal solution for the wholesale price and the market price can be obtained according to the first-order condition, i.e.

$$w^{HH*}=\frac{a-bc_m-b\Delta c_m+3bc_s+3b\Delta c_s}{4b} \quad (24)$$

$$p^{HH*}=\frac{3a+bc_{s+m}+b\Delta c_{s+m}}{4b} \quad (25)$$

The profits of suppliers and manufacturers are expressed respectively as：

$$\pi_s^{HH*}=\frac{(a-bc_{s+m}-b\Delta c_{s+m})^2}{16b} \quad (26)$$

$$\pi_m^{HH*}=\frac{(a-bc_{s+m}-b\Delta c_{s+m})^2}{8b} \quad (27)$$

Proposition 4 suggests that in the HH case, the optimal wholesale price w is positively related to the supplier's opportunity cost Δc_m and negatively related to the manufacturer's opportunity cost Δc_s; the optimal market price p is positively related to both parties' opportunity costs, and the profits of both are negatively related to either of their opportunity costs.

5. Comparative analysis

By comparing and analysing the optimal results of suppliers and manufacturers in different scenarios, the following conclusions can be drawn.

Corollary1.① when $\Delta c_{s+m} \geq A_1$, if $\lambda_m \geq A_2$, then $w^{HH} \geq w^{NN}$; if $\lambda_m < A_2$, then $w^{HH} < w^{NN}$. when $\Delta c_{s+m} < A_1$, then $w^{HH} > w^{NN}$.

② if $\lambda_m \geq A_3$, then $w^{HH} \geq w^{HN}$; if $\lambda_m < A_3$, then $w^{HH} < w^{HN}$.

③ if $\lambda_s \geq A_4$, then $w^{HH} \leq w^{NH}$; if $\lambda_s < A_4$, then $w^{HH} > w^{NH}$.

Among them

$$A_1 = \frac{(4b\lambda_s\sigma_s^2 + 8)\Delta c_s - (a - bc_{s+m})\lambda_s\sigma_s^2}{b\lambda_s\sigma_s^2 + 2};$$

$$A_2 = \frac{(2b\lambda_s\sigma_s^2 + 4)\Delta c_{s+m} - (8b\lambda_s\sigma_s^2 + 16)\Delta c_s + 2(a - bc_{s+m})\lambda_s\sigma_s^2}{(a - bc_{s+m} + 4b\Delta c_s - b\Delta c_{s+m})\sigma_m^2}; A_3 = \frac{4\Delta c_m}{(a - bc_{s+m} - b\Delta c_{s+m})\sigma_m^2};$$

$$A_4 = \frac{6\Delta c_s}{(a - bc_{s+m} - 2b\Delta c_s - b\Delta c_{s+m})\sigma_s^2}.$$

From **Corollary 1**, the wholesale price in the HH case is higher than the wholesale price in the NN and HN cases if the manufacturer's risk aversion factor λ_m is above the threshold when the opportunity cost Δc_{s+m} is higher. If the supplier risk aversion factor is higher than a certain threshold, the wholesale price in the HH case is lower than that in the NH case, and if the supplier risk is lower than the threshold, the wholesale price in the HH case is higher than that in the NH case. However, when the opportunity cost is small and even tends to zero, it can be found that the threshold value of the risk factor at this time is also numerically smaller or even tends to zero. At this point, the wholesale price in the HH case is always higher than in the NN and HN cases and lower than in the NH case.

Corollary2.① when $\Delta c_{s+m} \geq B_1$, if $\lambda_m \geq B_2$, then $p^{HH} \leq p^{NN}$; if $\lambda_m < B_2$, then $p^{HH} > p^{NN}$ .when $\Delta c_{s+m} < B_1$, then $p^{HH} < p^{NN}$.

② if $\lambda_m \geq A_3$, then $p^{HH} \leq p^{HN}$; if $\lambda_m < A_3$; then $p^{HH} > p^{HN}$.

③ if $\lambda_s \geq B_3$, then $p^{HH} \leq p^{NH}$;if $\lambda_s < B_3$, then $p^{HH} > p^{NH}$.

Among them

$$\frac{(a - bc_{s+m})\lambda_s\sigma_s^2}{b\lambda_s\sigma_s^2 + 2} = B_1; \frac{(2b\lambda_s\sigma_s^2 + 4)\Delta c_{s+m} - 2(a - bc_{s+m})\lambda_s\sigma_s^2}{(a - bc_{s+m} - b\Delta c_{s+m})\sigma_m^2} = B_2;$$

$$\frac{2\Delta c_s}{(a - bc_{s+m} - b\Delta c_{s+m})\sigma_s^2} = B_3.$$

From **Corollary 2**, it can be seen that when the opportunity cost is high, the market price in the HH case is lower than in the NN and HN cases if the manufacturer's risk aversion factor is above a certain threshold. If the supplier risk aversion factor is higher than a certain threshold, the market price in the HH case is lower than in the NH case, and if the supplier risk is lower than the threshold, the market price in the HH case is higher than in the NH case. However, when the opportunity cost is small or even converges to zero, the wholesale price in the HH case is always lower than in the NN, HN, and NH cases.

Corollary 3.① when $\Delta c_{s+m} \geq C_1$,if $\lambda_m \geq C_2$, then $\pi_s^{HH} > U_s^{NN}$,if $\lambda_m < C_2$,then $\pi_s^{HH} < U_s^{NN}$. when $\Delta c_{s+m} < C_1$, then $\pi_s^{HH} > U_s^{NN}$.

② if $\lambda_m \geq A_3$, then $\pi_s^{HH} > U_s^{HN}$; if $\lambda_m < A_3$, then $\pi_s^{HH} < U_s^{HN}$.

③ if $\lambda_s \geq C_3$, then $\pi_s^{HH} > \pi_s^{NH}$; if $\lambda_s < C_3$, then $\pi_s^{HH} < \pi_s^{NH}$.

Among them

$$\frac{(\sqrt{b\lambda_s\sigma_s^2+2}-\sqrt{2})(a-bc_{s+m})}{b\sqrt{b\lambda_s\sigma_s^2+2}} = C_1 ; \frac{2(\sqrt{2b\lambda_s\sigma_s^2+4}(a-bc_{s+m})-(b\lambda_s\sigma_s^2+2)(a-bc_{s+m}-b\Delta c_{s+m}))}{(a-bc_{s+m}-b\Delta c_{s+m})b\sigma_m^2} = C_2 ;$$

$$\frac{2\Delta c_s(2a-2bc_{s+m}-b\Delta c_m-b\Delta c_{s+m})}{(a-bc_{s+m}-b\Delta c_{s+m})^2\sigma_s^2} = C_3 .$$

Corollary 3 suggests that the HH scenario is most favourable to the supplier if the opportunity cost is large enough and the risk aversion factor of the supplier or manufacturer is also large. However, the HH scenario is most unfavorable to the supplier when the risk factor of the supplier or manufacturer is relatively small. This is because it is more profitable for both or only one party to hedge than for both parties to hedge. However, if the opportunity cost is relatively small or even tends to zero, then one should choose to hedge regardless of one's own and the other's risk factors. An interesting phenomenon in this reasoning is that the manufacturer's and supplier's risk factor thresholds are cost-adjusted, with opportunity cost having the greatest impact, reflecting the influence of opportunity cost on supply chain members' strategic choices, and hedging is usually the best option when opportunity cost is large.

Corollary 4.① when $\Delta c_{s+m} \geq D_1$, if $\lambda_m \geq D_2$, then $\pi_m^{HH} \geq U_m^{NN}$; if $\lambda_m < D_2$,then $\pi_m^{HH} < U_m^{NN}$; when $\Delta c_{s+m} < D_1$, then $\pi_m^{HH} > U_m^{NN}$.

② if $\lambda_m \geq D_3$, then $\pi_m^{HH} \geq U_m^{HN}$; if $\lambda_m < D_3$, then $\pi_m^{HH} < U_m^{HN}$.

③ if $\lambda_s \geq C_3$, then $\pi_m^{HH} \geq U_m^{NH}$; if $\lambda_s < C_3$, then $\pi_m^{HH} < U_m^{NH}$.

Among them

$$\frac{\left(b\lambda_s\sigma_s{}^2+2-\sqrt{2b\lambda_s\sigma_s{}^2+4}-2\right)\left(-bc_{s+m}+a\right)}{b\left(b\lambda_s\sigma_s{}^2+2\right)} = D_1 ;$$

$$\frac{2((b\lambda_s\sigma_s^2+2)(2a-2bc_{s+m}-b\Delta c_{s+m})\Delta c_{s+m}-\lambda_s\sigma_s^2(a-bc_{s+m})^2)}{(a-bc_{s+m}-b\Delta c_{s+m})\sigma_m^2} = D_2 ;$$

$$\frac{4\Delta c_m(2a-2bc_{s+m}-b\Delta c_s-b\Delta c_{s+m})}{(a-bc_{s+m}-b\Delta c_{s+m})\sigma_m^2} = D_3 .$$

Corollary 4 has the same conclusion as **Corollary 3**. Similarly, for a manufacturer, scenario HH is the best strategy for the supplier when the opportunity cost is large enough and the risk factor for the supplier or manufacturer is large. When the risk factor for the supplier or manufacturer is small, the scenario HH is the worst option for the supplier. However, if the opportunity cost is relatively small or even tends to zero, then the hedge should be chosen regardless of the risk factor of oneself and the other party. The fact that the two inferences have the same conclusion indicates that the interests of the supply chain members in this study are aligned, and this point can promote better cooperation between the two parties throughout the chain of activities to ensure that the interests of both parties are maximised.

6. Analysis of examples

In this section, the impact of different hedging strategies on the decision maker's strategy choice is compared using an arithmetic analysis. And the impact of the risk factors of suppliers and manufacturers on their optimal profits at different opportunity costs is also explored. Here, the values of the parameters of the model are set according to the possible situations of the firm as : $a = 100$; $b = 2$; $\sigma_s = 0.2$; $\sigma_m = 0.15$; $c_s = 1.2$; $c_m = 1.6$.

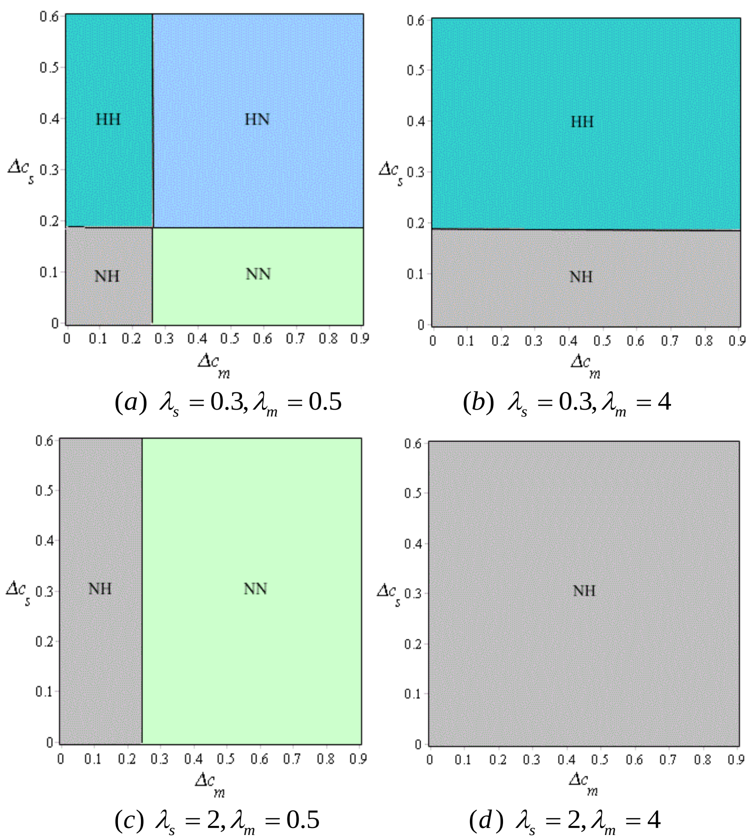
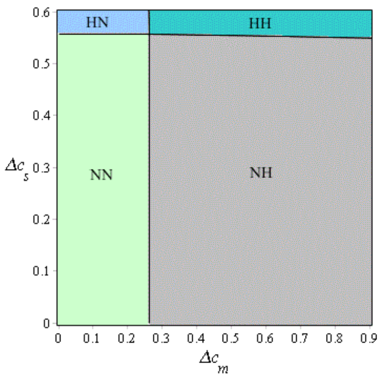
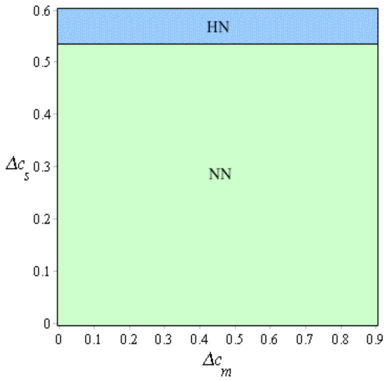


Figure 1. Effect of opportunity cost on wholesale price with different risk factors

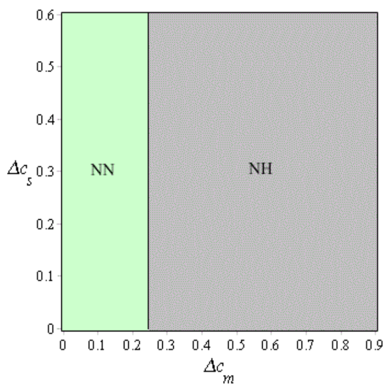
In **Figure 1**, it can be seen that when the risk coefficients of both suppliers and manufacturers are low, the lower the opportunity cost of both parties, the higher the wholesale price in the NH case; if only the opportunity cost of the manufacturer is elevated, the highest wholesale price in the NN case; the opposite is true if only the opportunity cost of the supplier is elevated. When the opportunity cost of both parties is higher, the wholesale price is the highest in the HN case only. As the risk factor increases for both, the moderating effect of the opportunity cost on wholesale prices becomes smaller. This is demonstrated by the fact that, regardless of the change in opportunity cost, the wholesale price is highest when the supplier does not hedge and the manufacturer does.



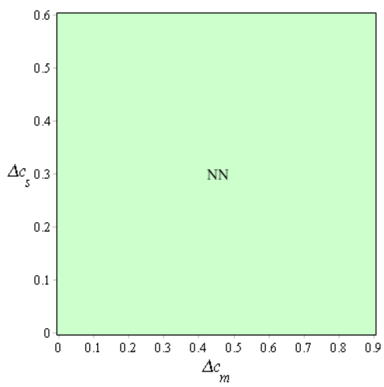
$(a)\ \lambda_s = 0.3, \lambda_m = 0.5$



$(b)\ \lambda_s = 0.3, \lambda_m = 4$



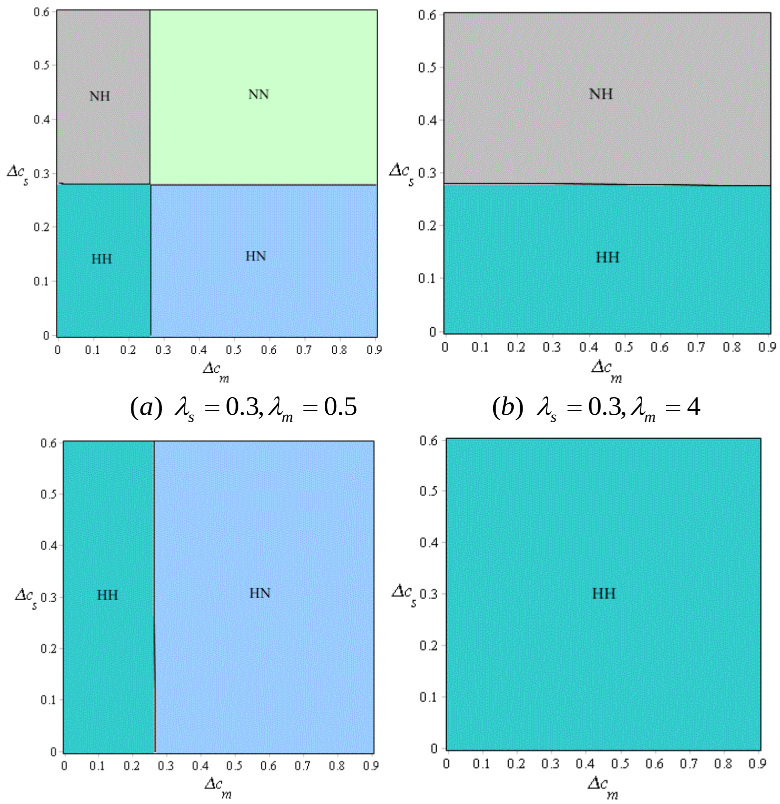
$(c)\ \lambda_s = 2, \lambda_m = 0.5$



$(d)\ \lambda_s = 2, \lambda_m = 4$

Figure 2 Effect of opportunity cost on market price with different risk factors

The interval in **Figure 2** shows that the risk aversion coefficient and the opportunity cost have little effect on the regulation of market prices. We can find that when both risk aversion coefficients are small, the higher the preference for hedging, the higher the market price as the opportunity cost increases. This may seem unconventional, but combined with **Figure 1**, we can find that both tend to pass the opportunity cost downstream when hedging due to their small risk aversion coefficients. As the risk factor increases, the opportunity cost will no longer moderate the price. At this point, the market price is highest when neither chooses to hedge**.**



$(a)\ \lambda_s = 0.3, \lambda_m = 0.5$ $(b)\ \lambda_s = 0.3, \lambda_m = 4$

$(c)\ \lambda_s = 2, \lambda_m = 0.5$ $(d)\ \lambda_s = 2, \lambda_m = 4$

Figure 3 Impact of opportunity cost on supplier strategy with different risk factors

Figure 3 suggests that the manufacturer can disregard the opportunity cost of the supplier when both the manufacturer's and the supplier's risk factors are low. He should choose to hedge when his opportunity cost is low and give up when it is high. As his risk factor increases, it is in his best interest not to hedge, regardless of changes in the other party's parameters. And as the other party's risk factor increases, he should also refer to his opportunity cost; the smaller the opportunity cost, the more suitable hedging is for participation. When the risk aversion factor is a large value for both parties, he should firmly choose to hedge to maximise his interests, regardless of the change in opportunity cost.

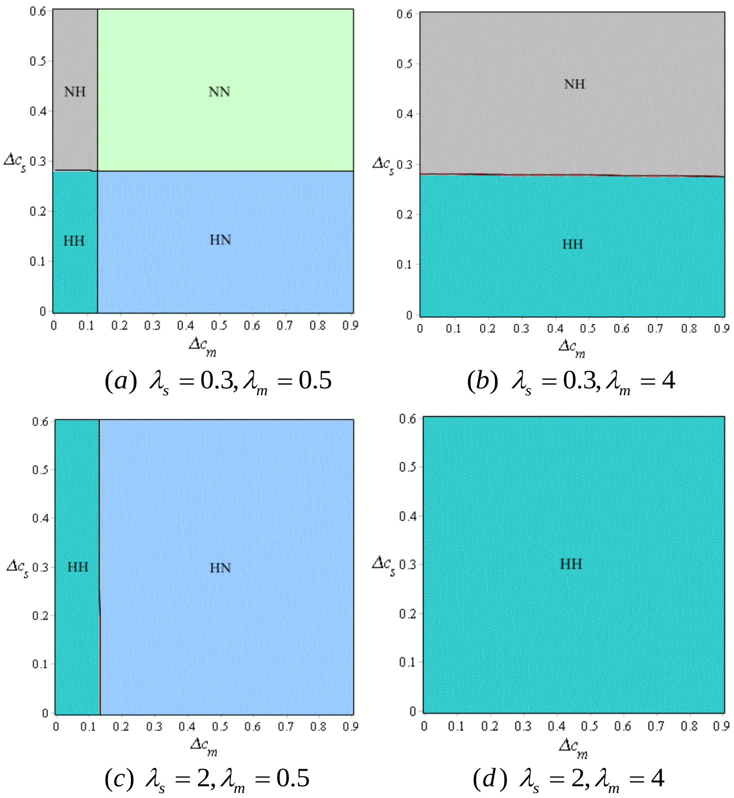


Figure 4. Effect of opportunity cost on manufacturer's strategy with different risk factors

Figure 4 is roughly the same as **Figure 3**. However, the difference is that although the suppliers and manufacturers have roughly the same strategic choices, they have some different value ranges. This suggests that, in some cases, neither of them can maximise benefits simultaneously. Because supply chain coordination is relative, in the case of independent decision-making, even if the information is symmetric, each party cannot maximise benefits at the same time.

7. Conclusion and Future

In this paper, we study a two-level supply chain consisting of suppliers and manufacturers who are risk-averse. Four different hedging strategies are used. Under these strategies, the optimal hedging strategy for each member is explored.

The optimal strategy choice for profit maximisation was analysed by comparing the profit of each member under these four strategies. Theoretical and numerical analyses were then performed, and the following conclusions were obtained.

First, whether hedged or not, a firm's opportunity cost and risk factor will always have a positive impact on the price determined by that firm. Suppliers transfer their own risk and opportunity cost to downstream suppliers through the wholesale price, while manufacturers transfer it to the market. Furthermore, hedging is not beneficial for all companies. The choice of specific strategies requires a combination of risk aversion factors and opportunity costs for both firms and counterparties. Additionally, as parameters, both the risk aversion coefficient and the opportunity cost moderate the strategic choices of the supply chain members. However, when either parameter is very large or small, the moderation of strategy by the other parameter loses its significance. Finally, the opportunity cost and the degree of risk are consistent for the strategic choice of supply chain members with is, which promotes cooperation between members to some extent. With the change in the risk degree and the opportunity cost, the strategic choice of each supply chain member is not the same in value, but the direction of strategic choice is roughly the same, which ensures that the supply chain members have the willingness to cooperate.

Our study was limited to one supplier and one manufacturer, which has some limitations. Future studies could be extended to multiple suppliers or multiple manufacturers.

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