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Analysis of Conditional Value-at-Risk for Newsvendor with Holding and Backorder Cost under Market Search

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Abstract: We consider a distribution system with one supplier and two retailers. For the two retailers, they face different demand and are both risk averse. We study a single period model which the supplier has ample goods and the retailers order goods separately. Market search is measured as the fraction of customers who unsatisfied with their "local" retailer due to stock-out, and search for the goods at the other retailer before leaving the system. We investigate how the retailers game for order quantity in a Conditional Value-at-Risk framework and study how risk averse degree, market search level, holding cost and backorder cost influence the optimal order strategies. Furthermore, we use uniform distribution to illustrate these results and obtain Nash equilibrium of order strategies.

Key words: risk averse; Conditional Value-at-Risk; market search; game theory
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0 Introduction

Traditionally, supply chain models focus on the optimization of the expected total profit, or the expected total cost over a planning horizon. We consider a single period scenario of a distribution system in which a single supplier provides one kind of product to two retailers infinitely. The customer's demand of each retailer is random, and when the demand can not be met by one retailer because of stock-out, the customer may go to the other retailer. This phenomenon is often referred to as "market search". A related concept that has been studied in the literature is "substitutable product"[1, 2]. Since the two retailers compete for the demand, the order decision of one retailer may affect the demand of the competing retailer, thereby creating a strategic interaction between the retailers' order decisions. In this paper, we analyze the order strategies of the two retailers when they compete for customers in a Conditional Value-at-Risk(CVaR) framework with market search. Furthermore, we use uniform distribution to illustrate these results and study how risk averse degree, market search level, holding cost and backorder cost influence the optimal order strategies.

In the field of economics and finance, agents are often assumed to be risk averse and they maximize a concave utility of wealth. Mean-variance analysis is an important operational approach to deal with risk aversion[3]. There have been some attempts in the supply chain such as Refs.[4-8]. Most of SCM literatures focus on the criteria of minimizing expected cost or maximizing expected profit. But for risk averse problem, the literatures often focus on the criteria of maximizing expected profit.

Ref.[8] studies the channel coordination with a risk-averse retailer and a risk-neutral supplier. For a newsvendor with downside risk, it gives simple analysis. Ref.[6] considers a number of basic inventory models with mean-variance method. It shows that the systematic mean-variance trade-off analysis can be carried out efficiently, and introduces a efficient frontier constraint.

It is well known that there are three major risk formulations are widely used in finance literatures: Mean-Variance and its variants, Value-at-Risk(VaR) and Conditional Value-at-Risk (CVaR).

The CVaR criterion[9,10], which measures the average value of profit falling below the η-quantile level, has better computational characteristics and surfaces in the financial and insurance literature. CVaR measure ignores the contributions of profit beyond the specified quantile, and focuses on the average profits from the lower quantile. For the case of profit maximization, the η-CVaR under an inventory policy μ defined as

$$\mathrm{CVaR}_\eta(f(\mu,D)) = E[f(\mu,D) \leqslant q_\eta(f(\mu,D))] \quad (1)$$

which $f(\mu,D)$ is the profit function under evaluation with control policy μ, and perturbation on demand D, $q_\eta(Z)$ is the η-quantile of a random variable Z defined as follows:

$$q_\eta(Z) = \inf\{z \mid P(Z \leqslant z) \geqslant \eta\}.$$

A more general definition of CVaR

$$\mathrm{CVaR}_\eta(f(\mu,D)) = \max_{v\in\mathbf{R}}\{v + \frac{1}{\eta}E[\min(f(\mu,D)-v,0)]\} \quad (2)$$

The two definitions can be shown equivalent and the latter is more convenient to computer.

Most recently papers to our work is Refs.[11,12], in the former paper, they assume supplier and two retailers are risk neutral and analyze the order strategies of the two retailers when they compete for both the supplier's capacity and customers. In the latter paper, the authors compared two systems: in one system, retailers hold stocks separately and in the other other system, retailers cooperate to centralize stocks at a single location under market search.

1 Model Description

We consider a one-period setting in which a single supplier having ample goods sells one kind of product to two retailers who have the same risk averse degree η. The two retailers face the different markets, the customer's demand at each retailer is random, and when the demand cann't be met by one retailer because of stock-out, the customer may go to the other retailer. This phenomenon is often referred to as "market search". We assume the demand is D_i which is a continuous random variable for a stochastic local demand of retailer $i(i=1,2)$, the corresponding probability density function and cumulative distribution function are $f_i(\bullet)$ and $F_i(\bullet)$ respectively. The two retailers sell a unit product to customers at price p, each retailer purchases goods from supplier at a unit price w, per unit backorder cost b for lost sale, and per unit holding cost h for excess inventory. For simplicity, we assume no salvage value. Retailer i orders m_i from the supplier. Customers encountering a stock-out at retailer 1 will visit retailer 2 with probability α and at retailer 2 will visit retailer 1 with probability β. Thus, for retailer i, the total demand consists of customers who visit retailer i firstly and customers who switch from retailer $j(i \neq j)$ due to stock-out. The former is called local demand, the latter distant demand, and the sum of these two, i.e., the total demand facing retailer i, effective demand at retailer i denoted by R_i, therefore

$$\begin{cases} R_1 = D_1 + \beta(D_2 - m_2)^+ \\ R_2 = D_2 + \alpha(D_1 - m_1)^+ \end{cases} \quad (3)$$

where $(x)^+ = \max\{x,0\}$. Then the retailer 1's profit is:

$$\pi_{R_1}(m_1,m_2) = (p-w+b)m_1 - (p+h+b)(m_1-R_1)^+ - bR_1 \quad (4)$$

and the retailer 2's profit is:

$$\pi_{R_2}(m_1,m_2) = (p-w+b)m_2 - (p+h+b)(m_2-R_2)^+ - bR_2 \quad (5)$$

Since the function $(x)^+$ is convex in x, consequently, $\pi_{R_1}(m_1,m_2)$ is concave in m_1 for any given m_2 and $\pi_{R_2}(m_1,m_2)$ is concave in m_2 for any given m_1. For symmetry, in the following we will only analyze retailer 1's order decision in detail. With a Conditional Value-at-Risk (CVaR) criterion at the retailer, the objective of retailer 1 is to find the best response order quantity $m_1^*(m_2)$ given retailer 2's order quantity m_2 which solves

$$\max_{m_1} \mathrm{CVaR}_\eta(\pi_{R_1}(m_1,m_2)) = E[\pi_{R_1}(m_1,m_2) \mid \pi_{R_1}(m_1,m_2) \leqslant q_\eta(\pi_{R_1}(m_1,m_2))] \quad (6)$$

where

$$q_\eta(\pi_{R_1}(m_1,m_2)) = \inf\{x : P(\pi_{R_1}(m_1,m_2) \leqslant x) \geqslant \eta\} \quad (7)$$

Define a concave function:

$$g(m_1,m_2,v) = v + \frac{1}{\eta}E\min\{\pi_{R_1}(m_1,m_2) - v, 0\} \quad (8)$$

Therefore, from (2), given retailer 2's order quantity, retailer 1's optimal order quantity $m_1^*(m_2)$ is to solve the following equation:

$$m_1^*(m_2) = \arg\max_{m_1} \max_{v} g(m_1, m_2, v) \tag{9}$$

From (3) and (8), we can obtain:

$$g(m_1, m_2, v) = v + \frac{1}{\eta} E\min\{\pi_{R_1}(m_1, m_2) - v, 0\}$$

$$= v - \frac{1}{\eta} E[v - \pi_{R_1}(m_1, m_2)]^+$$

$$= v - \frac{1}{\eta}\int_0^\infty \int_0^\infty \{v - (p - w + b)m_1 + (p + h + b)[m_1 - x_1 - \beta(x_2 - m_2)^+]^+ + b[x_1 + \beta(x_2 - m_2)^+]\}^+ \mathrm{d}F_1(x_1)\mathrm{d}F_2(x_2) \tag{10}$$

Let

$$G(m_1, m_2, v) = \int_0^\infty \int_0^\infty \{v - (p - w + b)m_1 + (p + h + b)[m_1 - x_1 - \beta(x_2 - m_2)^+]^+ + b[x_1 + \beta(x_2 - m_2)^+]\}^+ \mathrm{d}F_1(x_1)\mathrm{d}F_2(x_2)$$

$$= \int_0^{m_1}\int_0^{m_2} [v + (h + w)m_1 - (p + h)x_1]^+ \mathrm{d}F_2(x_2)\mathrm{d}F_1(x_1)$$

$$+ \int_{m_1}^\infty \int_0^{m_2} [v - (p - w + b)m_1 + bx_1]^+ \mathrm{d}F_2(x_2)\mathrm{d}F_1(x_1)$$

$$+ \int_{m_2}^\infty \int_0^{m_1 - \beta(x_2 - m_2)} \{v + (h + w)m_1 - (p + h)[x_1 + \beta(x_2 - m_2)]\}^+ \mathrm{d}F_1(x_1)\mathrm{d}F_2(x_2)$$

$$+ \int_{m_2}^\infty \int_{m_1 - \beta(x_2 - m_2)}^\infty \{v - (p - w + b)m_1 + b[x_1 + \beta(x_2^+ - m_2)]\}\mathrm{d}F_1(x_1)\mathrm{d}F_2(x_2) \tag{11}$$

Lemma 1 Given retailer 1's order quantity m_1, and retailer 2's order quantity m_2, $g(m_1, m_2)$ can be maximized at v^* which can be obtained by solving the following equation

$$F_2(m_2)F_1\left(\frac{v + (h + w)m_1}{p + h}\right) + \left[1 - F_1\left(m_1 + \frac{(p - w)m_1 - v}{b}\right)\right]F_2(m_2)$$
$$+ \int_{m_2}^\infty F_1\left(m_1 - \beta(x_2 - m_2) + \frac{v - (p - w)m_1}{p + h}\right)\mathrm{d}F_2(x_2)$$
$$+ \int_{m_2}^\infty \left[1 - F_1\left(m_1 - \beta(x_2 - m_2) - \frac{v - (p - w)m_1}{b}\right)\right]\mathrm{d}F_2(x_2) = \eta.$$

Proof From (8) and (11), we have

Case 1 $v \leqslant (p - w)m_1$.

$$G(m_1, m_2, v) = \int_0^{\frac{v + (h + w)m_1}{p + h}} \int_0^{m_2} \{v + (h + w)m_1 - (p + h)x_1\}\mathrm{d}F_2(x_2)\mathrm{d}F_1(x_1)$$

$$+ \int_{m_1 + \frac{(p - w)m_1 - v}{b}}^\infty \int_0^{m_2} [v - (p - w + b)m_1 + bx_1]\mathrm{d}F_2(x_2)\mathrm{d}F_1(x_1)$$

$$+ \int_{m_2}^\infty \int_0^{m_1 - \beta(x_2 - m_2) + \frac{v - (p - w)m_1}{p + h}} \{v + (h + w)m_1 - (p + h)[x_1 + \beta(x_2 - m_2)]\}\mathrm{d}F_1(x_1)\mathrm{d}F_2(x_2)$$

$$+ \int_{m_2}^\infty \int_{m_1 - \beta(x_2 - m_2) - \frac{v - (p - w)m_1}{b}}^\infty \{v - (p - w + b)m_1 + b[x_1 + \beta(x_2 - m_2)]\}\mathrm{d}F_1(x_1)\mathrm{d}F_2(x_2) \tag{12}$$

then

$$g(m_1, m_2, v) = v - \frac{1}{\eta} G(m_1, m_2, v) \tag{13}$$

Therefore, by taking the derivative with respect to v on both sides of (13), we obtain

$$\frac{\partial g(m_1, m_2, v)}{\partial v} = 1 - \frac{1}{\eta}\left\{F_2(m_2)F_1\left(\frac{v + (h + w)m_1}{p + h}\right) + \left[1 - F_1\left(m_1 + \frac{(p - w)m_1 - v}{b}\right)\right]F_2(m_2)\right.$$
$$+ \int_{m_2}^\infty F_1\left(m_1 - \beta(x_2 - m_2) + \frac{v - (p - w)m_1}{p + h}\right)\mathrm{d}F_2(x_2)$$
$$\left.+ \int_{m_2}^\infty \left[1 - F_1\left(m_1 - \beta(x_2 - m_2) - \frac{v - (p - w)m_1}{b}\right)\right]\mathrm{d}F_2(x_2)\right\} \tag{14}$$

It follows that

$$\begin{cases} \dfrac{\partial g(m_1, m_2, v)}{\partial v}\Big|_{v = (p - w)m_1} = 1 - \dfrac{1}{\eta} \leqslant 0 \\ \dfrac{\partial g(m_1, m_2, v)}{\partial v}\Big|_{v = -\infty} = 1 \end{cases} \tag{15}$$

Then we have the optimal value $\bar{v}$ which satisfies the first order condition, i.e. $\bar{v}$ satisfies the following equation,

$$F_2(m_2)F_1\left(\frac{v + (h + w)m_1}{p + h}\right) + \left[1 - F_1\left(m_1 + \frac{(p - w)m_1 - v}{b}\right)\right]F_2(m_2)$$
$$+ \int_{m_2}^\infty F_1\left(m_1 - \beta(x_2 - m_2) + \frac{v - (p - w)m_1}{p + h}\right)\mathrm{d}F_1(x_1)$$
$$+ \int_{m_2}^\infty \left[1 - F_1\left(m_1 - \beta(x_2 - m_2) - \frac{v - (p - w)m_1}{b}\right)\right]\mathrm{d}F_2(x_2) = \eta \tag{16}$$

Case 2 $v > (p - w)m_1$

$$G(m_1, m_2, v) = \int_0^{m_1}\int_0^{m_2} \{v + (h + w)m_1 - (p + h)x_1\} \cdot \mathrm{d}F_2(x_2)\mathrm{d}F_1(x_1)$$

$$+ \int_{m_1}^\infty \int_0^{m_2} [v - (p - w + b)m_1 + bx_1]\mathrm{d}F_2(x_2)\mathrm{d}F_1(x_1)$$

$$+ \int_{m_2}^\infty \int_0^{m_1 - \beta(x_2 - m_2)} \{v + (h + w)m_1 - (p + h)[x_1 + \beta(x_2 - m_2)]\} \cdot \mathrm{d}F_1(x_1)\mathrm{d}F_2(x_2)$$

$$+ \int_{m_2}^\infty \int_{m_1 - \beta(x_2 - m_2)}^\infty \{v - (p - w + b)m_1 + b[x_1 + \beta(x_2 - m_2)]\} \cdot \mathrm{d}F_1(x_1)\mathrm{d}F_2(x_2) \tag{17}$$

then

$$g(m_1, m_2, v) = v - \frac{1}{\eta} G(m_1, m_2, v) \tag{18}$$

Therefore, by taking the derivative with respect to v on both sides of (18), we obtain

$$\frac{\partial g(m_1,m_2,v)}{\partial v}\Big|_{v=(p-w)m_1}=1-\frac{1}{\eta}\leqslant 0$$

Combining case 1 with case 2, we can obtain the optimal value $v^*=\bar{v}$.

Theorem 1 (i) Given retailer 2's order quantity m_2, let retailer 1's best response order quantity be $m_1^*(m_2)$, which satisfies

$$F_1(m_1+\frac{(p-w)m_1-v^*}{b})F_2(m_2)+\int_{m_2}^{\infty}F_1(m_1-\beta(x_2-m_2)-\frac{v^*-(p-w)m_1}{b})\mathrm{d}F_2(x_2)=1-\frac{(h+w)\eta}{p+h+b}$$

(ii) Given retailer 1's order quantity m_1, let retailer 2's best response order quantity be $m_2^*(m_1)$, which satisfies

$$F_2(m_2+\frac{(p-w)m_2-v^*}{b})F_1(m_1)+\int_{m_1}^{\infty}F_2(m_2-\alpha(x_1-m_1)-\frac{v^*-(p-w)m_2}{b})\mathrm{d}F_1(x_1)=1-\frac{(h+w)\eta}{p+h+b}$$

Proof (i) From Lemma 1, we have $m_1^*(m_2)=\arg\max_{m_1} g(m_1,m_2,v^*)$. By taking the derivative with respect to m_1 on $g(m_1,m_2,v^*)$ and using (16), we obtain

$$\frac{\partial g(m_1,m_2,v^*)}{\partial m_1}=-(h+w)+\frac{p+h+b}{\eta}\{1-F_2(m_2)\cdot F_1(m_1+\frac{(p-w)m_1-v^*}{b})-\int_{m_2}^{\infty}F_1(m_1-\beta(x_2-m_2)-\frac{v^*-(p-w)m_1}{b})\mathrm{d}F_2(x_2)\} \quad (19)$$

Let $m_1^*(m_2)$ satisfies the first order condition of (19), which satisfies the following equation,

$$F_1(m_1+\frac{(p-w)m_1-v^*}{b})F_2(m_2)+\int_{m_2}^{\infty}F_1(m_1-\beta(x_2-m_2)-\frac{v^*-(p-w)m_1}{b})\mathrm{d}F_2(x_2)=1-\frac{(h+w)\eta}{p+h+b}$$

Therefore, we have completed (i).

(ii) The same argument as (i).

2 Game Analysis of under Uniform Distribution

In this section, we analyze how much the two retailers will order under the demand D_1, D_2 which are both uniformly distributed in an interval [0, S], and we can obtain Nash equilibrium of the two retailers' order quantity using a numerical examples. Furthermore, we also study how risk averse degree η, market search level α, β, hoding cost h and backorder cost b influence the two retailers' optimal order quantity. By (16) and Lemma 1, we can immediately obtain the following proposition.

Proposition 1 If the demand D_1, D_2 are both uniformly distributed in an interval [0, S], then $v^*=(p-w)m_1-\frac{bS(1-\eta)(p+h)}{P+h+b}$.

With Proposition 1 in hand, we can write out the best response order quantity as follows,

Proposition 2 (i) Given retailer 2's order quantity m_2, retailer 1's best response order quantity is

$$m_1^*(m_2)=\frac{\beta}{2S}(m_2-S)^2+\frac{b+(p-w)\eta}{p+h+b}S$$

(ii) Given retailer 1's order quantity m_1, retailer 2's best response order quantity is

$$m_2^*(m_1)=\frac{\alpha}{2S}(m_1-S)^2+\frac{b+(p-w)\eta}{p+h+b}S$$

Therefore, Fig. 1 shows the relation of the two retailers' best response order quantity when given the other retailer's order quantity. From Fig.1, we can find there exists a Nash equilibrium. Then we will verify the result using a specific numerical example.

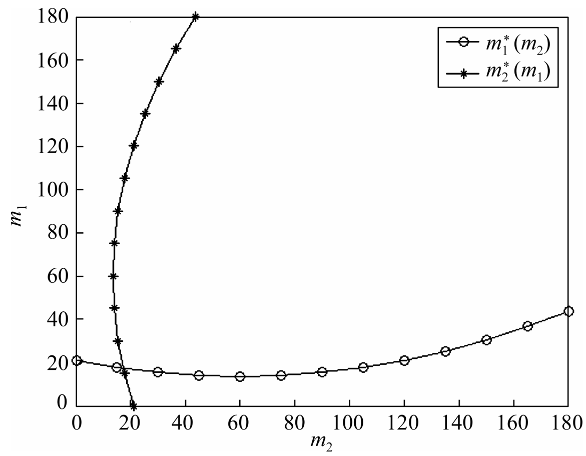

Fig.1 Optimal order quantity

Now we present some numerical examples to verify our analysis and illustrate the optimal order strategies. In our example, the demand process is specified by uniform distribution in an interval [0, 60]. The selling price $p=8$ and the wholesale price $w=3$. While analyzing the impact of risk averse degree η, we set α={0.25, 0.50, 0.75}, β={0.25, 0.50, 0.75}, $h=b$=1, and vary η from 0 to 1. While investigating the impact of the market search, we fix α=0.25, $h=b=1$, η={0.25, 0.50, 0.75} and vary β from 0 to 1. While studying the impact of holding cost or backorde cost, we fix one parameter to equal to 1, and let the other change. Our intention is to examine how the optimal Nash equilibrium is influenced by η, market search, holding cost and backorder cost. The following Table 1, Table 2 show that the optimal Nash equilibrium when α, β and η change from 0 to 1 and $h = b = 1$.

Table 1 Optimal Nash equilibrium when the market search factors are symmetric

$\alpha=\beta$	η	(m_1^*, m_2^*)	$\alpha=\beta$	η	(m_1^*, m_2^*)	$\alpha=\beta$	η	(m_1^*, m_2^*)
	0	(11.00, 11.00)		0	(14.59, 14.59)		0	(17.37, 17.36)
	0.10	(13.50, 13.50)		0.10	(16.78, 16.78)		0.10	(19.34, 19.34)
	0.25	(17.30, 17.30)		0.25	(20.13, 20.13)		0.25	(22.36, 22.36)
0.25	0.50	(23.74, 23.74)	0.50	0.50	(25.86, 25.86)	0.75	0.50	(27.57, 27.57)
	0.75	(30.33, 30.33)		0.75	(31.81, 31.81)		0.75	(33.04, 33.04)
	0.90	(34.37, 34.37)		0.90	(35.50, 35.50)		0.90	(36.46, 36.46)
	0.99	(36.82, 36.82)		0.99	(37.76, 37.76)		0.99	(38.57, 38.57)
	1.00	(37.09, 37.09)		1.00	(38.01, 38.01)		1.00	(38.81, 38.81)

Table 2 Optimal Nash equilibrium when the market search factors are asymmetric

α	β	η	(m_1^*, m_2^*)	α	β	η	(m_1^*, m_2^*)
		0	(16.44,9.95)			0	(22.28,8.96)
		0.10	(18.36,12.61)			0.10	(23.54,11.77)
		0.25	(21.34,16.61)			0.25	(25.62,15.96)
0.25	0.50	0.50	(26.60,23.32)	0.25	0.75	0.50	(29.59,22.93)
		0.75	(32.22,30.10)			0.75	(34.17,29.89)
		0.90	(35.77,34.22)			0.90	(37.20,34.08)
		0.99	(37.96,36.71)			0.99	(39.12,36.61)
		1.00	(38.21,36.99)			1.00	(39.34,36.89)

From Table 1 and Table 2, we find that there always exists a unique Nash equilibrium between the two retailers in a conditional value-at-risk with market search. In Fig.2, we want to study how risk averse degree and market search level influence the optimal order strategies. We set η as *X*-label, and $m = m_1^* = m_2^*$ as *Y*-label.

Figure 2 reports the two retailers' symmetric optimal Nash equilibrium when η changes from 0 to 1 and market search α, β change. We find that the simulated symmetric Nash equilibrium increases when one of η, α, β increases. When η approaches to 1, we find that market search α, β have a little influence on the symmetric Nash equilibrium.

In Fig.3, we fix α, set β as *X*-label, and m_1^* or m_2^* as *Y*-label. The curve of m_1^* is denoted by real line, and m_2^* is denoted by dashed.

Figure 3 reports how the market search affects the Nash equilibrium. Fixed α and η, m_1^* will increase with the market search β, but m_2^* will decrease with it. When η increases, the trend will be flatter.

Figure 4 illustrates how the holding cost affect the Nash equilibrium. When α, β and *b* are fixed, order quantity will decrease as the holding cost increasing. Order quantity and the difference of order quantity between two different holding cost will increase as η increasing.

Fig.5 shows how the backorder cost affect the Nash equilibrium. When α, β and *h* are fixed, order quantity

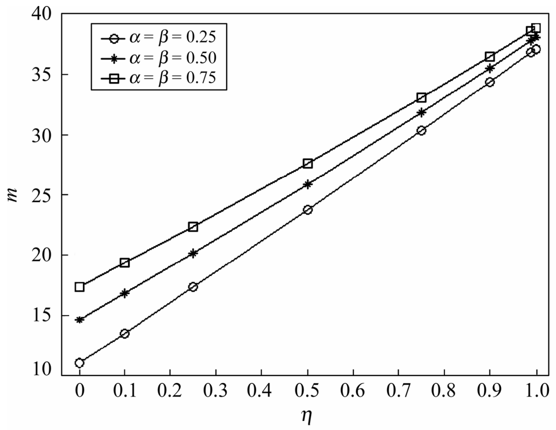

Fig.2 Symmetric order quantity

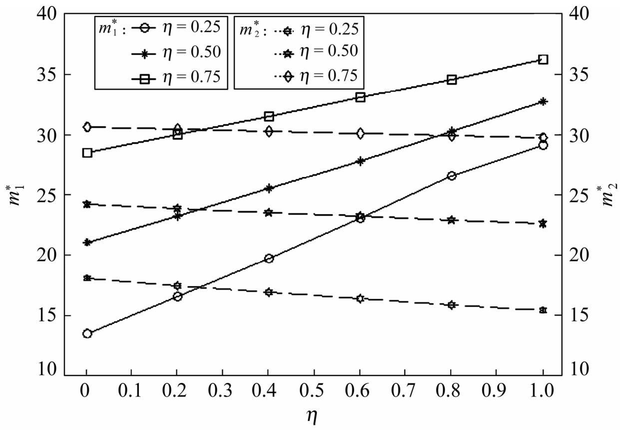

Fig.3 Asymmetric order quantity

will increase as the backorder cost increasing. While η increasing, order quantity will increase, but the difference of order quantity between two different backorder cost will decrease.

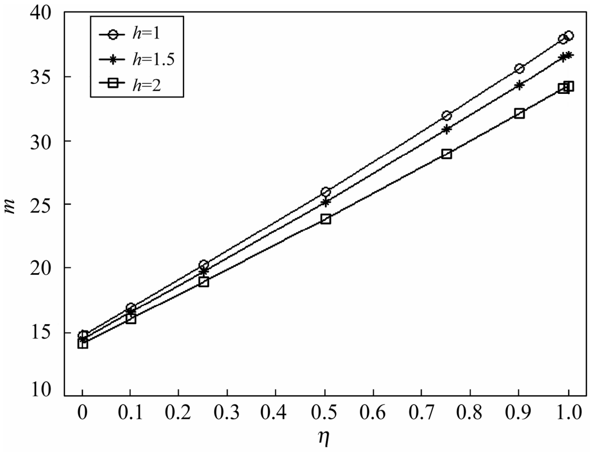

Fig.4 Holding cost affecting

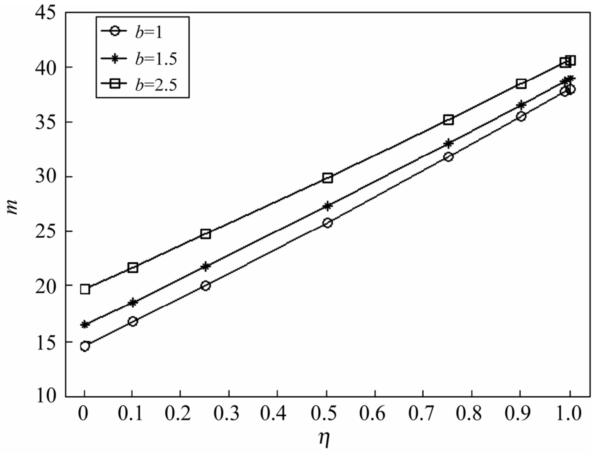

Fig.5 Backorder cost affecting

3 Conclusion

In this paper, we consider a simple supply chain in which a single supplier sells one item to two retailers. The supplier has infinite capacity, and retailers order goods in a conditional value-at-risk with market search. We apply game theory to do research on the optimal order strategies of two retailers who are both risk averse under market search in a distribution system. Our model demonstrates how the retailers game for order quantity in a Conditional Value-at-Risk framework. We use uniform distribution to illustrate the impact of risk averse degree, market search level, holding cost and backorder cost. All the results conform to our intuition.

So far, we assume the two retailers are both risk averse, if they have different risk attitude or the supplier has limit capacity, there maybe something more interesting to happen. In the future, we will investigate these problems. Another welcome extension would be to consider competition in a dynamic multi-period model.

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