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The Loss-Averse Newsvendor Problem with Random Yield and Reference Dependence

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Abstract: This paper studies a loss-averse newsvendor problem with reference dependence, where both demand and yield rate are stochastic. We obtain the loss-averse newsvendor's optimal ordering policy and analyze the effects of loss aversion, reference dependence, random demand and yield on it. It is shown that the loss-averse newsvendor's optimal order quantity and expected utility decreases in loss aversion level and reference point. Then, that this order quantity may be larger than the risk-neutral one's if the reference point is less than a negative threshold. In addition, although the effect of random yield leads to an increase in the order quantity, the loss-averse newsvendor may order more than, equal to or less than the classical one, which significantly depends on loss aversion level and reference point. Numerical experiments were conducted to demonstrate our theoretical results.

Keywords: newsvendor problem; random yield; loss aversion; reference dependence

1. Introduction

The newsvendor problem is a fundamental decision-making model in operations management and has attracted much scholarly attention over the decades. Nevertheless, most previous studies mainly focused on the randomness in demand, while ignoring the supply uncertainty. In fact, supply risk has been increasingly significant in recent years and seriously undermines the operational performance and profits. Many factors, such as equipment malfunctions in production process and damage during transportation, often result in the supply uncertainty, and then the quantity received by the newsvendor is different from that ordered. For example, a semiconductor manufacturer in the high-tech industries often suffers a very high yield loss that is usually more than 50% [1]. Another example occurs in agriculture and the perishable fruit and vegetables often suffer a loss in transit. As a result, the newsvendor indeed is confronted by both demand and supply uncertainties, and should consider these two factors simultaneously when he makes the order decisions. Treatment of supply risk has been an important topic in analyzing inventory management, and extensive reviews of the literature on random yield models are provided by Yano and Lee [2] and Grosfeldnir and Gerchak [3].

In addition, the decision makers are assumed to be risk-neutral and the expected profit maximizers in most of the newsvendor-type models. However, many practical examples show they are bounded rationality and the actual order quantities are deviating from the optimal solution, which is referred to as "decision bias" (e.g., [4–7]). Then Kahneman and Tversky [8] propose prospect theory and explain this phenomenon. They suggest that the outcome is separated into gains and losses using a reference point (i.e., reference dependence), and the decision makers facing equivalent gains and losses are more averse to the latter (i.e., loss aversion). Since prospect theory can better characterize the individual choice behavior under risk, many researchers introduce it into inventory management and study the loss-averse newsvendor models, while most of them only take into account the demand uncertainty. Although several works (e.g., [9,10]) consider the supply risk simultaneously, the reference point is set to zero in the loss aversion utility function and thus its effect is ignored. However, some existing studies have revealed that reference dependence plays an important role in explaining the decision bias and has a significant effect on the order decisions (e.g., [11,12]). Therefore, it is meaningful to study the loss-averse newsvendor's ordering policy when both supply uncertainty and reference dependence are considered. The purpose of our study is to shed light on the following problems: (1) How does the loss-averse newsvendor with reference dependence make order decisions under uncertain demand and supply? (2) How would the newsvendor's optimal order quantity and expected utility change if the loss aversion level or reference point were to vary? (3) How do the demand and yield uncertainties affect the order decisions? (4) What are the joint effects of loss aversion, reference dependence and supply risk on the order quantity?

To address the above problems, we studied a loss-averse newsvendor problem with reference dependence and stochastically proportional yield, a typical supply risk under which the yield is the product of random yield rate and order quantity. This approach of modeling supply uncertainty is widely used in the literature (e.g., [10,13,14]), and can apply in a case in which batch size is relatively large or its variation is small, etc. [2]. To the best of our knowledge, this model has not been considered in the literature. The loss-averse newsvendor's optimal ordering policy in the presence of reference dependence and random yield is first obtained herein. Then we analyze the effects of loss aversion, reference dependence, random demand and yield on it, and also derive the managerial insights on their joint effects. The loss-averse newsvendor's order quantity may be larger than the risk-neutral one's if the reference point is less than a negative threshold. In addition, although the effect of random yield drives the order quantity up, the loss-averse newsvendor may order more than, equal to or less than the classical one, which heavily depends on loss aversion level and reference point. These results demonstrate the significance of considering reference dependence.

The rest of this paper is organized as follows. In Section 2, we review the newsvendor problem with loss aversion and reference dependence, as well as uncertain supply. In Section 3, we formulate the problem. In Section 4, we obtain the optimal ordering policy and study the impacts of different factors on it. In Section 5, we conduct numerical experiments to illustrate our results. In Section 6, we conclude our paper.

2. Literature Review

We review the literature on the newsvendor problem from the following three aspects: loss aversion, reference dependence and supply uncertainty. Note that the existing studies only consider one or two factors, whereas we build a comprehensive model by jointly considering those three factors.

The first stream is on the newsvendor problem based on loss aversion. Schweitzer and Cachon [15] is a seminal paper on this problem and shows that loss-averse preferences lead to a decrease in the order quantity. Then this problem has attracted much attention and been studied in various contexts in recent years. Wang and Webster [16] extend their model by considering shortage cost and find that the loss-averse newsvendor may order more than the risk-neutral one. Wang [17] assumed multiple loss-averse newsvendors order from a single supplier and studied the newsvendor game under the proportional demand allocation rule. Liu et al. [13] also investigated the game in which two loss-averse newsvendors compete for substitutable demand. Both studies found the supply chain inventory understocking would occur if the effect of loss aversion was strong enough and dominated that of competition. Xu et al. [18] investigated the newsvendor's option purchase decision when the excess demands could be replenished. When only the mean and variance of the demand distribution were known, Yu et al. [19] considered the robust newsvendor problem and obtained the robust optimal ordering policy. Moreover, some researchers consider the loss-averse newsvendor's risk management and introduce CVaRmeasure into this problem. Xu et al. [20] studied the loss-averse newsvendor problem, wherein the objective is to maximize the CVaR of utility, and present some insights for the risk management of loss-averse newsvendor. Xu et al. [21] considered the newsvendor problem with backordering, and found the optimal order quantity with the CVaR objective was smaller than that maximizing expected utility.

The second stream is on the newsvendor problem with reference dependence. Herweg [22] studied the expectation-based loss-averse newsvendor problem, wherein the overall utility consists of realized profit and gain-loss utility. Long and Nasiry [11] demonstrated that prospect theory can explain the newsvendor's ordering behavior observed in experiments when the reference point is considered. Wu et al. [23] studied the competitive newsvendor problem in the case of proportional demand allocation and demand reallocation. They showed that the total inventory level in the decentralized case may be lower than that in the centralized case. Wang and Wang [24] proposed a reference dependence utility function to study the newsvendor problem, and showed that the loss-averse newsvendor may order more than the classical one. Mandal et al. [25] investigated the joint pricing and ordering problem under an inventory-dependent demand. Bai et al. [26] also considered this problem under a price-dependent demand. They found both demand and reference point types have a heavy impact on the optimal decisions. Uppari and Hasija [27] built several newsvendor models under different reference point types and found that mean demand, as a stochastic reference point, outperformed others.

The third stream is on the newsvendor problem with supply uncertainty, in which random yield and random supply capacity are two main forms of modeling supply risk. Gerchak et al. [28] studied the periodic review model with random yield and obtained the optimal ordering policy in each period. Wang and Gerchak [29] extended their work when random supply capacity was also considered. He [30] analyzed how a firm made price and production quantity decisions under random yield. Lee and Lu [31] studied two firms' inventory competition when the yield was random and demand was substitutable. Shi et al. [32] investigated the effect of supply process improvement on the newsvendor's decision when capacity was random. Moreover, some researchers incorporated the loss-averse preferences into this problem. Liu et al. [33] studied the loss-averse newsvendor problem with random yield, while considering both shortage cost and no shortage cost, respectively. Ma et al. [14] assumed that yield rate follows a binomial distribution and also investigated this problem. Regarding both supplier and retailer having loss-averse preferences, Du et al. [10] considered a two-echelon supply chain with random yield and obtained the supplier's and retailer's optimal policies. Liu et al. [34] investigated a periodic review inventory problem with loss-averse retailer and random supply capacity. Nevertheless, all those studies set a zero reference point and ignored the effect of reference dependence, which is the key factor of prospect theory.

3. Model Description

We consider a single-period inventory problem with random yield and loss-averse newsvendor (retailer). Before the selling season, the newsvendor makes an order quantity decision. The supplier responds to provide the quantity the newsvendor orders and the lead time is zero. Due to the issues that may arise in production and transit, there are some defective units in the products delivered. Assuming the fraction of good units (yield rate) is random, the available quantity is the product of yield rate and initial order quantity. The newsvendor only needs to pay for this quantity rather than the quantity ordered. The leftover inventory at the end of the season is salvaged and any unsatisfied demand is lost. The notation concerned in this paper is listed in Table 1.

Table 1. Summary of the notation.

Notation	Description
p	Selling price per unit,
c	Purchasing cost per unit,
s	Salvage value per unit, $p > c > s$,
Q	Order quantity,
X	Random demand. Its probability density function is $f(x)$ and cumulative distribution function is $F(x)$,
Y	Yield rate, then the available quantity is YQ. Its probability density function is $g(y)$ and mean is μ,
w_0	Target profit per unit (reference point),
λ	Loss aversion level,
Q^*	Optimal order quantity,
Q_1^*	Optimal order quantity of the risk-neutral newsvendor,
Q_2^*	Optimal order quantity under deterministic yield,
Q_3^*	Optimal order quantity of the classical newsvendor.

For the realized market demand x and yield rate y, the newsvendor's profit under the order quantity Q is

$$\pi(Q,x,y) = \begin{cases} (p-c)yQ, & x \geq yQ, \\ (p-s)x - (c-s)yQ, & x < yQ. \end{cases} \tag{1}$$

The newsvendor is loss-averse and we employ the following piecewise-linear utility function:

$$U(\pi) = \begin{cases} \pi - \pi_0, & \pi \geq \pi_0, \\ \lambda(\pi - \pi_0), & \pi < \pi_0, \end{cases} \tag{2}$$

where $\lambda \geq 1$ is the newsvendor's loss aversion level and π_0 is his reference point that makes him change risk attitude. That is, there is a kink at π_0, and the newsvendor will perceive gains if $\pi \geq \pi_0$, whereas he will perceive losses if $\pi < \pi_0$. When $\lambda = 1$ and $\pi_0 = 0$, our model reduces to the risk-neutral one. Note that although multiple forms of loss aversion utility function are presented (e.g., [15,24,35,36]), among them this piecewise-linear one is most widely used in the economics, finance (e.g., [37,38]) and operations management literature (e.g., [15–21,23,24,26]) because of its simplicity. Nevertheless, π_0 is generally set to zero in (2), and we will consider the non-zero case.

In the inventory models with reference dependence, target gross profit is the main setting for π_0. For example, Long and Nasiry [11] and Mandal et al. [25] used a convex combination of the newsvendor's maximum and minimum possible payoff. It follows from (1) that if the newsvendor's minimum possible payoff is $(s-c)yQ$ and the maximum possible payoff is $(p-c)yQ$, the reference point (target gross profit) depends on the order quantity and yield rate in this setting. However, the decision maker usually has a clear and definite target in practice. In view of this, Wu et al. [23] and Bai et al. [26] suggest that it is easier and more realistic for the newsvendor to choose the target unit profit instead of target gross profit as reference point. Similarly to them, we introduce a target unit profit $w_0 \in [s-c, p-c]$ as the reference point, where the minimum $s-c<0$ is the loss per unit unsold product and the maximum $p-c>0$ is the revenue per unit selling product. Then the target gross profit $\pi_0 = w_0 yQ$. Moreover, Bai et al. [26] also clearly state that this setting for the reference point is consistent with that in Long and Nasiry [11]. When combining with (1), the utility function (2) can be formulated as

$$U(\pi(Q,x,y)) = \begin{cases} (p-c-w_0)yQ, & x \geq yQ, \\ (p-s)x - (c-s+w_0)yQ, & \frac{c-s+w_0}{p-s} yQ \leq x < yQ, \\ \lambda[(p-s)x - (c-s+w_0)yQ], & 0 \leq x < \frac{c-s+w_0}{p-s} yQ. \end{cases} \tag{3}$$

The newsvendor's expected utility is (as shown in Figure 1)

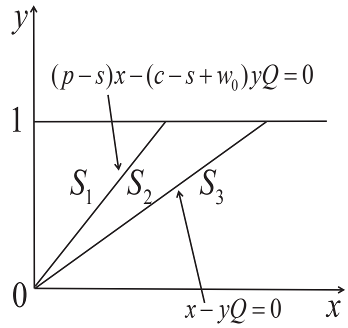

Figure 1. A graphical presentation of demand and yield rate outcomes.

$$\begin{aligned}
E[U(\pi(Q,X,Y))] &= \int_0^1 \int_0^\infty U(\pi(Q,x,y))f(x)g(y)dxdy \\
&= \lambda \iint_{S_1} [\pi(Q,x,y)-\pi_0]f(x)g(y)dxdy + \iint_{S_2 \cup S_3} [\pi(Q,x,y)-\pi_0]f(x)g(y)dxdy \\
&= (\lambda-1)\int_0^1 \int_0^{\frac{c-s+w_0}{p-s}yQ} [(p-s)x-(c-s+w_0)yQ]f(x)g(y)dxdy \\
&\quad + \int_0^1 \int_0^{yQ} [(p-s)x-(c-s+w_0)yQ]f(x)g(y)dxdy \\
&\quad + \int_0^1 \int_{yQ}^\infty (p-c-w_0)yQf(x)g(y)dxdy.
\end{aligned} \tag{4}$$

The newsvendor's objective is to choose an order quantity Q that maximizes the expected utility $E[U(\pi(Q,X,Y))]$. Note that Liu et al. [33] studied a similar problem wherein the reference point was zero, and we extend their model to the non-zero case.

4. Optimal Policy and Analysis

The loss-averse newsvendor's optimal ordering policy when considering random yield and reference dependence is as follows.

Proposition 1. *The newsvendor's expected utility $E[U(\pi(Q,X,Y))]$ is concave in Q, and there exists a unique optimal order quantity Q^* that satisfies*

$$(\lambda-1)(c-s+w_0)\int_0^1 yF\left(\tfrac{c-s+w_0}{p-s}yQ^*\right)g(y)dy + (p-s)\int_0^1 yF(yQ^*)g(y)dy = (p-c-w_0)\mu. \tag{5}$$

Proof. It follows from (4) that the first-order and second-order partial derivatives of $E[U(\pi(Q,X,Y))]$ with respect to Q are

$$\begin{aligned}
\frac{\partial E[U(\pi(Q,X,Y))]}{\partial Q} &= -(\lambda-1)(c-s+w_0)\int_0^1 yF\left(\frac{c-s+w_0}{p-s}yQ\right)g(y)dy \\
&\quad -(p-s)\int_0^1 yF(yQ)g(y)dy + (p-c-w_0)\mu,
\end{aligned} \tag{6}$$

and

$$\begin{aligned}
\frac{\partial^2 E[U(\pi(Q,X,Y))]}{\partial Q^2} &= -\frac{(\lambda-1)(c-s+w_0)^2}{p-s}\int_0^1 y^2 f\left(\frac{c-s+w_0}{p-s}yQ\right)g(y)dy \\
&\quad -(p-s)\int_0^1 y^2 f(yQ)g(y)dy < 0,
\end{aligned} \tag{7}$$

respectively. Thus $E[U(\pi(Q,X,Y))]$ is concave. Since $\frac{\partial E[U(\pi(Q,X,Y))]}{\partial Q}\Big|_{Q=0} = (p-c-w_0)\mu \geq 0$ and $\frac{\partial E[U(\pi(Q,X,Y))]}{\partial Q}\Big|_{Q\to\infty} = -\lambda(c-s+w_0)\mu \leq 0$, setting (6) equal to 0 gives a unique optimal order quantity Q^*; that is, Q^* satisfies (5). □

This proposition shows that the newsvendor's optimal order quantity significantly depends on loss aversion level, reference point, random demand and yield. Next we discuss the effects of those factors on it in detail.

4.1. The Effect of Loss Aversion

The following proposition characterizes how the optimal solution and expected utility change when loss aversion level increases.

Proposition 2. *For any given w_0, the newsvendor's optimal order quantity Q^* and expected utility $E[U(\pi(Q^*,X,Y))]$ are decreasing in λ.*

Proof. Let

$$\begin{aligned} M(Q^*) =& (\lambda-1)(c-s+w_0)\int_0^1 yF\left(\frac{c-s+w_0}{p-s}yQ^*\right)g(y)dy \\ &+(p-s)\int_0^1 yF(yQ^*)g(y)dy-(p-c-w_0)\mu. \end{aligned} \tag{8}$$

Its partial derivatives with respect to Q^* and λ are

$$\frac{\partial M(Q^*)}{\partial Q^*} = \frac{(\lambda-1)(c-s+w_0)^2}{p-s}\int_0^1 y^2 f\left(\frac{c-s+w_0}{p-s}yQ^*\right)g(y)dy+(p-s)\int_0^1 y^2 f(yQ^*)g(y)dy > 0, \tag{9}$$

and

$$\frac{\partial M(Q^*)}{\partial \lambda} = (c-s+w_0)\int_0^1 yF\left(\frac{c-s+w_0}{p-s}yQ^*\right)g(y)dy > 0. \tag{10}$$

Applying the implicit function theorem to $M(Q^*)=0$ yields

$$\frac{dQ^*}{d\lambda} = -\frac{\partial M(Q^*)}{\partial\lambda}\Bigg/\frac{\partial M(Q^*)}{\partial Q^*} < 0, \tag{11}$$

thus Q^* is decreasing in λ.

When the order quantity is Q^*, it follows from (4) that

$$\begin{aligned} \frac{dE[U(\pi(Q^*,X,Y))]}{d\lambda} =& \frac{\partial E[U(\pi(Q^*,X,Y))]}{\partial\lambda}+\frac{\partial E[U(\pi(Q^*,X,Y))]}{\partial Q^*}\cdot\frac{dQ^*}{d\lambda} \\ =& \int_0^1\int_0^{\frac{c-s+w_0}{p-s}yQ^*}[(p-s)x-(c-s+w_0)yQ^*]f(x)g(y)dxdy \leq 0, \end{aligned} \tag{12}$$

which implies that $E[U(\pi(Q^*,X,Y))]$ is decreasing in λ. □

This proposition shows that compared with risk neutrality ($\lambda=1$), loss-averse preferences ($\lambda>1$) drive the order quantity and expected utility down. The more loss-averse the newsvendor is, the less his order quantity is, which we refer to as the *loss aversion effect*. When loss aversion level increases, the newsvendor is more averse to losses. Then he will select a smaller order quantity to avoid the potential losses that come from the possible excess order. Note that the loss aversion effect is consistent with that found in many inventory models based on loss aversion (e.g., [13,14,17]).

4.2. The Effect of a Reference Point

We next study the effects of a reference point on the optimal solution and expected utility.

Proposition 3. *For any given λ, the newsvendor's optimal order quantity Q^* and expected utility $E[U(\pi(Q^*, X, Y))]$ are decreasing in w_0.*

Proof. It follows from (8) that

$$\begin{aligned}\frac{\partial M(Q^*)}{\partial w_0} =&(\lambda-1)\int_0^1 yF\left(\frac{c-s+w_0}{p-s}yQ^*\right)g(y)dy+\frac{(\lambda-1)(c-s+w_0)Q^*}{p-s}\\ &\int_0^1 y^2 f\left(\frac{c-s+w_0}{p-s}yQ^*\right)g(y)dy+\mu>0.\end{aligned} \tag{13}$$

Applying the implicit function theorem to $M(Q^*)=0$ and combining with (9) yields

$$\frac{dQ^*}{dw_0}=-\frac{\partial M(Q^*)}{\partial w_0}\bigg/\frac{\partial M(Q^*)}{\partial Q^*}<0; \tag{14}$$

thus, Q^* is decreasing in w_0.

When the order quantity is Q^*, we have

$$\begin{aligned}\frac{dE[U(\pi(Q^*,X,Y))]}{dw_0} =&\frac{\partial E[U(\pi(Q^*,X,Y))]}{\partial w_0}+\frac{\partial E[U(\pi(Q^*,X,Y))]}{\partial Q^*}\cdot\frac{dQ^*}{dw_0}\\ =&-(\lambda-1)Q^*\int_0^1 yF\left(\frac{c-s+w_0}{p-s}yQ^*\right)g(y)dy-\mu Q^*\le 0;\end{aligned} \tag{15}$$

then $E[U(\pi(Q^*, X, Y))]$ is decreasing in w_0. □

This proposition states that when the reference point increases, the newsvendor will order less products and thus his expected utility decreases. When the newsvendor selects a larger reference point, an outcome is more likely to be perceived as a loss and then ordering less can help hedge against the potential losses caused by overstocking. Moreover, compared with the zero reference point case, the effects of positive and negative reference points on the optimal order quantity are significantly different. More specifically, the newsvendor with positive reference point ($w_0 > 0$) orders less than the one with zero reference point ($w_0 = 0$), and the larger the reference point is, the less his order quantity is, which we refer to as the *positive reference point effect*. However, the newsvendor with a negative reference point ($w_0 < 0$) orders more than the one with a zero reference point, and the smaller the reference point is, the larger his order quantity is, which we refer to as the *negative reference point effect*. In short, the positive reference point effect induces the newsvendor to order less while the negative reference point effect induces him to order more.

4.3. Joint Effects of Loss Aversion and Reference Point

As shown in Propositions 2 and 3, when the reference point is positive, both loss aversion and reference point effects drive inventory down and thus the loss-averse newsvendor orders less than the risk-neutral one (zero reference point). However, when the reference point is negative, the reference point effect drives inventory up and may mitigate the loss aversion effect. To see how the loss aversion and reference point interact, we compare the optimal order quantity of the loss-averse newsvendor Q^* with that of the risk-neutral one Q_1^*. Note that when $\lambda = 1$ and $w_0 = 0$, Q^* reduces to Q_1^*, and from (5) we have

$$(p-s)\int_0^1 yF(yQ_1^*)g(y)dy=(p-c)\mu. \tag{16}$$

Let

$$L(w_0) = \left.\frac{\partial E[U(\pi(Q,X,Y))]}{\partial Q}\right|_{Q=Q_1^*} = -(\lambda-1)(c-s+w_0)\int_0^1 yF\left(\frac{c-s+w_0}{p-s}yQ_1^*\right)g(y)dy - (p-s)\int_0^1 yF(yQ_1^*)g(y)dy + (p-c-w_0)\mu. \tag{17}$$

Proposition 4. *For any given λ, the relation between Q^* and Q_1^* is as follows:*

(i) *When $0 \le w_0 \le p-c$, then $Q^* \le Q_1^*$.*
(ii) *When $s-c \le w_0 < 0$, there exists a unique $w_0^* \in [s-c, 0)$ that satisfies $L(w_0^*) = 0$. If $w_0 < w_0^*$, then $Q^* > Q_1^*$; if $w_0 = w_0^*$, then $Q^* = Q_1^*$; otherwise, $Q^* < Q_1^*$.*

Proof. When $0 \le w_0 \le p-c$, we have mentioned above that $Q^* \le Q_1^*$ due to both positive reference point and loss aversion effects.

When $s-c \le w_0 < 0$, since F is increasing, $L(w_0)$ is decreasing in w_0 and

$$L(s-c) = -(p-s)\int_0^1 yF(yQ_1^*)g(y)dy + (p-s)\mu = (p-s)\int_0^1 [1-F(yQ_1^*)]yg(y)dy > 0. \tag{18}$$

By combining that with (16), we have

$$\begin{aligned} L(0) =& -(\lambda-1)(c-s)\int_0^1 yF\left(\frac{c-s}{p-s}yQ_1^*\right)g(y)dy - (p-s)\int_0^1 yF(yQ_1^*)g(y)dy + (p-c)\mu \\ =& -(\lambda-1)(c-s)\int_0^1 yF\left(\frac{c-s}{p-s}yQ_1^*\right)g(y)dy < 0. \end{aligned} \tag{19}$$

Thus there exists a unique $w_0^* \in [s-c, 0)$ that satisfies $L(w_0^*) = 0$. If $w_0 < w_0^*$, then $L(w_0) > 0$. Since $E[U(\pi(Q,X,Y))]$ is concave and Q^* is the optimal solution, then $Q^* > Q_1^*$. Similarly, if $w_0 = w_0^*$, then $L(w_0) = 0$ and $Q^* = Q_1^*$; if $w_0 > w_0^*$, then $L(w_0) < 0$ and $Q^* < Q_1^*$. □

A loss-averse newsvendor with a zero reference point usually understocks (e.g., [14,34]), while Proposition 4 shows this does not always hold when the reference point is non-zero. When $0 \le w_0 \le p-c$, the loss-averse newsvendor's order quantity is less than the risk-neutral newsvendor's due to loss aversion and positive reference point effects. However, there exists a threshold of reference point w_0^* when $s-c \le w_0 < 0$. If $w_0 > w_0^*$, then the loss aversion effect that decreases the order quantity will dominate the negative reference point effect that increases the order quantity. The loss-averse newsvendor's order quantity is still less than the risk-neutral one's. If $w_0 = w_0^*$, then the loss aversion and reference point effects offset each other and their order quantities are equal. If $w_0 < w_0^*$, then the negative reference point effect is strong and will dominate the loss aversion effect. Thus the loss-averse newsvendor's order quantity is larger than the risk-neutral one's. This will never occur in most loss-averse newsvendor problems where reference dependence is ignored.

4.4. Effect of Random Demand

We now investigate the impact of the change to demand risk on the optimal order quantity by incorporating first-order stochastic dominance. When the demand distribution changes from $F(x)$ to $H(x)$, we say F first-order stochastically dominates H if $F(x) \le H(x)$ for all $x \in [0, \infty)$ [39]. That is, the random demand with distribution F is stochastically larger than that with distribution H. Let $E[U_F(\pi(Q,X,Y))]$ and $E[U_H(\pi(Q,X,Y))]$ denote the expected utilities when the demand distributions are $F(x)$ and $H(x)$, respectively. Q_F^* and Q_H^* are the corresponding optimal order quantity, respectively. Then the effect of random demand is as follows:

Proposition 5. *If F first-order stochastically dominates H in $[0,\infty)$, then $Q_F^* \geq Q_H^*$.*

Proof. Since $F(x) \leq H(x)$ for any $x \in [0,\infty)$, $F\left(\frac{c-s+w_0}{p-s}yQ\right) \leq H\left(\frac{c-s+w_0}{p-s}yQ\right)$ and $F(yQ) \leq H(yQ)$. It follows from (6) that $\frac{\partial E[U_H(\pi(Q,X,Y))]}{\partial Q}\Big|_{Q=Q_F^*} \leq \frac{\partial E[U_F(\pi(Q,X,Y))]}{\partial Q}\Big|_{Q=Q_F^*} = 0$. Then we have $Q_F^* \geq Q_H^*$ from the concavity of $E[U_H(\pi(Q,X,Y))]$. □

This proposition shows under the first-order stochastic dominance condition that the newsvendor will order more products when the demand is stochastically larger, which is intuitive.

4.5. The Effect of Random Yield

In the previous analysis, we assumed the yield was random. However, it is interesting to investigate the effect of random yield on the optimal decision. To do this, similarly to (4), the loss-averse newsvendor's expected utility in the case of deterministic yield is

$$\begin{aligned} E[U(\pi(Q,X))] =&(\lambda-1)\int_0^{\frac{c-s+w_0}{p-s}Q}[(p-s)x-(c-s+w_0)Q]f(x)dx \\ &+\int_0^{Q}[(p-s)x-(c-s+w_0)Q]f(x)dx+\int_Q^{\infty}(p-c-w_0)Qf(x)dx. \end{aligned} \tag{20}$$

It is easy to prove that $E[U(\pi(Q,X))]$ is concave and then the optimal order quantity Q_2^* satisfies the first-order condition, that is,

$$(\lambda-1)(c-s+w_0)F\left(\frac{c-s+w_0}{p-s}Q_2^*\right)+(p-s)F(Q_2^*)=p-c-w_0. \tag{21}$$

Proposition 6. *For any given λ and w_0, the newsvendor's optimal order quantity under random yield is larger than that under deterministic yield; i.e., $Q^* \geq Q_2^*$.*

Proof. Plugging Q_2^* into (6) and combining with (21), we have

$$\begin{aligned} \frac{\partial E[U(\pi(Q,X,Y))]}{\partial Q}\Big|_{Q=Q_2^*} =& -(\lambda-1)(c-s+w_0)\int_0^1 yF\left(\frac{c-s+w_0}{p-s}yQ_2^*\right)g(y)dy \\ &-(p-s)\int_0^1 yF(yQ_2^*)g(y)dy+(p-c-w_0)\mu \\ =&(\lambda-1)(c-s+w_0)\int_0^1 y\left[F\left(\frac{c-s+w_0}{p-s}Q_2^*\right)-F\left(\frac{c-s+w_0}{p-s}yQ_2^*\right)\right] \\ &g(y)dy+(p-s)\int_0^1 y[F(Q_2^*)-F(yQ_2^*)]g(y)dy \geq 0. \end{aligned} \tag{22}$$

Since $E[U(\pi(Q,X,Y))]$ is concave and Q^* is the optimal solution, $Q^* \geq Q_2^*$. □

This proposition implies that compared with the case of deterministic yield, yield uncertainty induces the newsvendor to order more products, which is consistent with our common sense and referred to as the *random yield effect*. When the yield is random, the available quantity the newsvendor actually receives is less than that he orders; thus, the newsvendor will order more products to hedge against the supply risk.

4.6. Joint Effects of Loss Aversion, Reference Point and Random Yield

Propositions 2, 3 and 6 show that random yield effect leads to an increase in the order quantity, whereas loss aversion and positive reference point effects lead to an decrease in the order quantity and may mitigate the inventory overstocking caused by yield uncertainty. To further investigate the joint effects of loss aversion, reference point and random yield on the order quantity, we next compare the optimal order quantity Q^* with the classical newsvendor solution Q_3^*. When $\lambda = 1$ and $w_0 = 0$ in (21), Q_2^* reduces to Q_3^* and satisfies

$$(p-s)F(Q_3^*) = p - c. \tag{23}$$

To facilitate the analysis, let

$$\begin{aligned} R(w_0) = \left.\frac{\partial E[U(\pi(Q,X,Y))]}{\partial Q}\right|_{Q=Q_3^*} &= -(\lambda-1)(c-s+w_0)\int_0^1 yF\left(\frac{c-s+w_0}{p-s}yQ_3^*\right)g(y)dy \\ &- (p-s)\int_0^1 yF(yQ_3^*)g(y)dy + (p-c-w_0)\mu. \end{aligned} \tag{24}$$

and

$$\lambda_0 = 1 + \frac{(p-s)\int_0^1 y[F(Q_3^*) - F(yQ_3^*)]g(y)dy}{(c-s)\int_0^1 yF\left(\frac{c-s}{p-s}yQ_3^*\right)g(y)dy}. \tag{25}$$

Proposition 7. *The relation between Q^* and Q_3^* is as follows:*

(i) *When $\lambda \le \lambda_0$, there exists a unique $w_0^{**} \in [0, p-c]$ that satisfies $R(w_0^{**}) = 0$. If $w_0 < w_0^{**}$, then $Q^* > Q_3^*$; if $w_0 = w_0^{**}$, then $Q^* = Q_3^*$; otherwise, $Q^* < Q_3^*$.*

(ii) *When $\lambda > \lambda_0$, there exists a unique $w_0^{**} \in [s-c, 0)$ that satisfies $R(w_0^{**}) = 0$. If $w_0 < w_0^{**}$, then $Q^* > Q_3^*$; if $w_0 = w_0^{**}$, then $Q^* = Q_3^*$; otherwise, $Q^* < Q_3^*$.*

Proof. It follows from (24) that $R(w_0)$ is decreasing in w_0, and we have

$$R(s-c) = -(p-s)\int_0^1 yF(yQ_3^*)g(y)dy + (p-s)\mu = (p-s)\int_0^1 y[1-F(yQ_3^*)]g(y)dy > 0, \tag{26}$$

and

$$R(p-c) = -\lambda(p-s)\int_0^1 yF\left(yQ_3^*\right)g(y)dy < 0. \tag{27}$$

Moreover, combining with (23) yields

$$\begin{aligned} R(0) &= -(\lambda-1)(c-s)\int_0^1 yF\left(\frac{c-s}{p-s}yQ_3^*\right)g(y)dy - (p-s)\int_0^1 yF(yQ_3^*)g(y)dy + (p-c)\mu \\ &= -(\lambda-1)(c-s)\int_0^1 yF\left(\frac{c-s}{p-s}yQ_3^*\right)g(y)dy + (p-s)\int_0^1 y[F(Q_3^*) - F(yQ_3^*)]g(y)dy. \end{aligned} \tag{28}$$

When $\lambda \le \lambda_0$, then $R(0) \ge 0$. Thus there exists a unique $w_0^{**} \in [0, p-c]$ that satisfies $R(w_0^{**}) = 0$. If $w_0 < w_0^{**}$, then $R(w_0) > 0$. Since $E[U(\pi(Q,X,Y))]$ is concave and Q^* is the optimal solution, then $Q^* > Q_3^*$. Similarly, if $w_0 = w_0^{**}$, then $R(w_0) = 0$ and $Q^* = Q_3^*$; if $w_0 > w_0^{**}$, then $R(w_0) < 0$ and $Q^* < Q_3^*$.

When $\lambda > \lambda_0$, then $R(0) < 0$ and there exists a unique $w_0^{**} \in [s-c, 0)$ that satisfies $R(w_0^{**}) = 0$. Thus part (ii) can be proved in a similar way. □

This proposition shows whether yield uncertainty leads to inventory overstocking depends on loss aversion level and reference point. It provides the sufficient condition under which the loss-averse newsvendor may order more than, equal to or less than the classical one (see Table 2). When loss aversion level is small (less than λ_0), there exists a positive threshold of reference point w_0^{**}, above which both the loss aversion and positive reference point effects that decrease the order quantity will dominate the random yield effect that increases the order quantity. Then compared with the classical one, the loss-averse newsvendor will order less products. If w_0 is equal to w_0^{**}, then they will order the same quantity. However, if w_0 belongs to $[0, w_0^{**})$, the random yield effect is strong and will dominate the loss aversion and positive reference point effects. In addition, if w_0 belongs to

$[s-c, 0)$, the random yield and negative reference point effects will dominate the loss aversion effect. Therefore, in these two cases, that is, when $w_0 \in [s-c, w_0^{**})$, the loss-averse newsvendor will order more products. On the other hand, when loss aversion level is large (larger than λ_0), there exists a negative threshold of reference point, below which both the random yield and negative reference point effects that increase the order quantity are strong and will dominate the loss aversion effect. Then the loss-averse newsvendor's order quantity is larger than the classical one's. Otherwise, the loss-averse newsvendor's order quantity is less than or equal to the classical one's.

Table 2. Relation between Q^* and Q_3^*.

	$\lambda \leq \lambda_0$				$\lambda > \lambda_0$			
w_0	$[s-c, 0)$	$[0, w_0^{**})$	w_0^{**}	$(w_0^{**}, p-c]$	$[s-c, w_0^{**})$	w_0^{**}	$(w_0^{**}, 0]$	$[0, p-c]$
Joint effects	R + N > L	R > L + P	L + P = R	L + P > R	R + N > L	R + N = L	L > R + N	L + P > R
Relation	$Q^* > Q_3^*$	$Q^* > Q_3^*$	$Q^* = Q_3^*$	$Q^* < Q_3^*$	$Q^* > Q_3^*$	$Q^* = Q_3^*$	$Q^* < Q_3^*$	$Q^* < Q_3^*$

R = random yield effect; N = negative reference point effect; P = positive reference point effect; L = loss aversion effect. The abbreviation "R + N > L" denotes "random yield and negative reference point effects dominate loss aversion effect", and other abbreviations in this row are explicated similarly.

5. Numerical Experiments

In this section, we carry out numerical experiments to illustrate the newsvendor's order decisions when loss aversion level and reference point change. Then the joint effects of loss aversion, reference dependence and random yield on the optimal order quantity are investigated. Let $p = 3$, $c = 2$ and $s = 1$. The demand X follows a truncated normal distribution with mean 100 and standard deviation 50, and the yield rate Y follows a uniform distribution with support [0, 1]. We conduct two sets of numerical experiments. In the first set, to illustrate the effects of loss aversion and reference point, we vary w_0 from $s-c = -1$ to $p-c = 1$ in steps of 0.05, and three different loss aversion levels are considered: $\lambda = 2$, $\lambda = 5$ and $\lambda = 8$. In the second set, to illustrate the joint effects of three factors, we vary w_0 from $s-c = -1$ to $p-c = 1$ in the cases of random and deterministic yields, respectively, and two different loss aversion levels are considered: $\lambda = 2$ and $\lambda = 8$.

Figure 2 shows the optimal order quantity with respect to the reference point under different loss aversion levels. Note that when $w_0 = s-c$, the newsvendor will always perceive gains and order more products; thus the optimal order quantity is ∞. On the other hand, when $w_0 = p-c$, the newsvendor will always perceive losses and it is better for him to order no products; thus, the optimal order quantity is 0. Thus, the curves become steeper when w_0 approaches its minimum $s-c$ or maximum $p-c$. For any given loss aversion level, the optimal order quantity decreases when the reference point increases. Moreover, for any given reference point, the optimal order quantity is decreasing in loss aversion level. That is, the larger the reference point (loss aversion level) is, the less the order quantity is, which confirms that both loss aversion and reference dependence have a significant impact on the order decisions. Those facts are in accordance with Propositions 2 and 3, and can be explained by the fact that ordering less helps hedge against the potential losses come from the possible excess order. Further, it is easy to calculate the risk-neutral newsvendor's optimal order quantity is $Q_1^* = 150.5$. This figure also illustrates when $\lambda = 2$, there exists a threshold of reference point $w_0^* = -0.1$. Compared with loss aversion effect, the negative reference point effect is strong and will dominate it when $w_0 < w_0^*$, and thus $Q^* > Q_1^*$. Otherwise, we have $Q^* \leq Q_1^*$. Similarly, in the case of $\lambda = 5$ and $\lambda = 8$, the thresholds are -0.25 and -0.35, respectively. These results are consistent with Proposition 4.

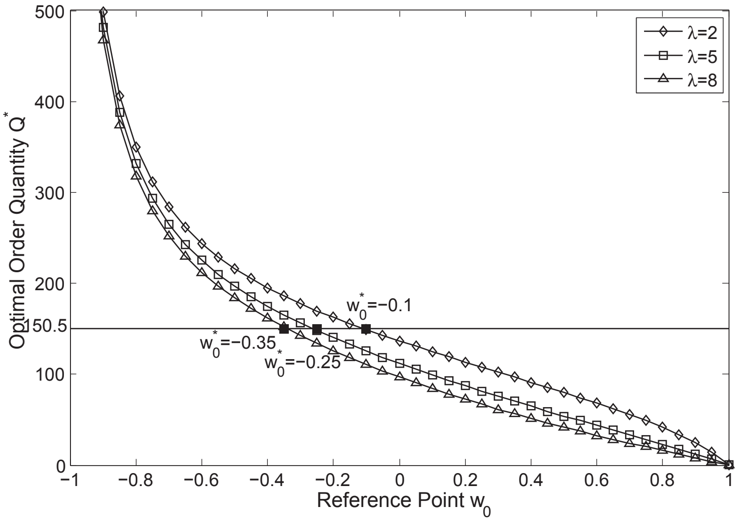

Figure 2. Optimal order quantity vs. reference point for different loss aversion levels.

Figure 3 illustrates the optimal order quantity with respect to the reference point under random and deterministic yields. As we can see, the order quantity decreases when the reference point increases, no matter whether yield is deterministic or random. For any given reference point and loss aversion level, the order quantity under random yield is larger than that under deterministic yield, which implies the yield uncertainty makes the newsvendor order more products. This is intuitive since the newsvendor will enhance the order quantity to hedge against it. It is also apparent that their difference is smaller when the reference point becomes larger, which indicates the random yield has a less significant effect. Moreover, the classical newsvendor's optimal order quantity is $Q_3^* = 101.4$. This figure also shows that when yield is random and λ is small ($\lambda = 2$), there exists a positive threshold of reference point $w_0^{**} = 0.3$, above which the loss aversion and positive reference point effects will dominate the random yield effect and then $Q^* < Q_3^*$. Otherwise, we have $Q^* \geq Q_3^*$. On the other hand, when λ is large ($\lambda = 8$), there exists a negative threshold of reference point $w_0^{**} = -0.05$, below which the negative reference point and random yield effects will dominate the loss aversion effect and $Q^* > Q_3^*$. Otherwise, we have $Q^* \leq Q_3^*$. These results are in accordance with Propositions 6 and 7. Note that although we restrict our consideration of truncated normal demand and uniform yield rate in the experiments, our results based on Propositions 2–4, 6 and 7 are independent of their distributions and parameter values.

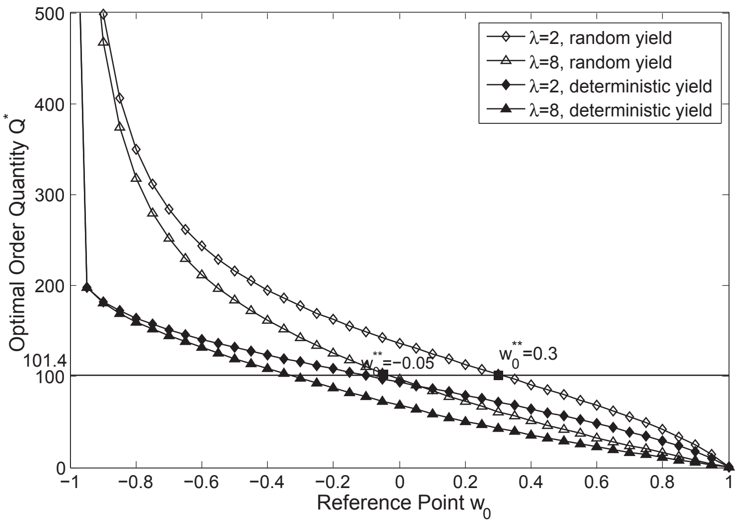

Figure 3. Optimal order quantity vs. reference point under random and deterministic yields.

6. Conclusions

In this paper, we investigate a loss-averse newsvendor problem with reference dependence where the yield rate is random. The newsvendor's ordering policy is first derived. It is shown that the optimal order quantity and expected utility are decreasing in loss aversion level and reference point, respectively. Then we examine the interaction effects of loss aversion and reference point on the optimal order quantity. There exists a negative threshold of reference point, above which the loss-averse newsvendor's order quantity is always less than the risk-neutral newsvendor's. However, if the reference point is less than this threshold, then the negative reference point effect that increases the order quantity will dominate the loss aversion effect that decreases the order quantity, and the loss-averse newsvendor's order quantity is larger. Then we analyze the impact of random demand on the optimal order quantity by incorporating first-order stochastic dominance. The newsvendor will order more products when the demand is stochastically larger. Further, we also find that compared with the case of deterministic yield, yield uncertainty induces the newsvendor to order more products. Then the overall effects of loss aversion, reference dependence and random yield are discussed. When the loss aversion level is small, there exists a positive threshold of reference point, above which both the loss aversion and positive reference point effects that decrease the order quantity will dominate the random yield effect that increases the order quantity. Then the loss-averse newsvendor will order less products than the classical one. Otherwise, he will order more. On the other hand, when loss aversion level is large, there exists a negative threshold of reference point, below which both the random yield and negative reference point effects will dominate the loss aversion effect, then the loss-averse newsvendor will order more products. Otherwise, he will order less. Thus, in contrast to Ma et al. [14] and Liu et al. [33], who studied the loss-averse newsvendor problem with random yield and zero reference point, our results indicate that reference dependence has a great impact on the newsvendor's decisions.

We only consider a single-period inventory problem. In the multi-period case, the reference point may change in different periods and affect the reorder point and optimal order quantity. How to determine the optimal ordering policy in each period will be a direction for future research. Furthermore, shortage cost was ignored to facilitate the analysis. When considering shortage cost, the reference point depends on the maximum demand, so the complexity of analysis is increased largely. Besides, as the loss aversion level increases, the newsvendor will order more products if the effect of stockout on profit dominates that of overstock. Thus, the joint effects of loss aversion, reference point and random yield may be significantly different from those in our paper. The model incorporating shortage cost deserves further study. Finally, our study is based on the assumption that the random demand and yield rate are independent. Another future research direction would be to consider their dependence and investigate how this would impact the whole analysis performed in this work.

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