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The newsvendor problem under multiplicative background risk

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Mots-clés : Problème du marchand de journaux, « background risk » multiplicatif, vulnérabilité au risque multiplicatif, fonction d'utilité dérivée, espérance d'utilité.
Keywords: Newsvendor problem, multiplicative background risk, multiplicative risk vulnerability, derived utility function, expected utility.

Résumé : Cette note étudie le problème du marchand de journaux sur une période lorsque le marchand de journaux fait face à un « background risk » multiplicatif neutre et indépendant dans un cadre d'espérance d'utilité. Il est montré que la vulnérabilité au risque multiplicatif est une condition suffisante pour garantir une baisse de l'ordre optimal. Une condition suffisante moins forte, plus commode à interpréter, est également proposée et discutée. Ce résultat permet de mieux comprendre les situations où un taux de change, d'imposition ou d'inflation, qui s'applique multiplicativement à la richesse finale, est effectif.

Abstract: This note studies the single-period newsvendor problem when the newsvendor faces a multiplicative neutral independent background risk in an expected utility framework. It is shown that multiplicative risk vulnerability is a sufficient condition to guarantee a decrease in the optimal order. A weaker sufficient condition which has more interpretability is also provided and discussed. This result sheds light on situations where exchange, tax or inflation rates risks, which apply multiplicatively to the final wealth, are at work.

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1 Introduction

The question examined in this paper is how a (independent) neutral multiplicative background risk (MBR), i.e. with mean equal to unity, affects the optimal order of the newsvendor in an expected utility framework. The introduction of a MBR can be thought as an inflation, a tax or a non-hedgeable exchange rate risk.[3] Despite a huge literature, both in economics and in operation research, the general issue of the newsvendor facing a multiplicative background risk has no been examined yet.

The so-called "newsvendor problem", also known as the "newsboy problem" is one of the standard of the OR literature and is described in many textbooks. In its simplest version it gives rise to the single-period problem (SPP) whose case is considered in the present paper. Amazingly, the consideration of risk preferences when studying this problem is much rare as noted in Khouja (1999). This is quite puzzling because decision in a SPP seem to be influenced by risk. Schweitzer and Cachon (2000) and Benzion *et al.* (2008) show that with comparison with the expected profit-maximizing newsvendor, choices in an experimental setting are systematically biased. Indeed, risk preferences are of primary importance when considering the SPP.[4]

The issues occasioned by the introduction of risk preferences in the SPP have received some treatment in the formal literatures of economics and OR. Important work relying on expected or non-expected utility includes that of Eeckhoudt *et al.* (1995), Keren and Pliskin (2006), Wang and Webster (2008) and Wang *et al.* (in press). Eeckhoudt *et al.* (1995) provide a number of comparative statics results when (i) the newsvendor is facing an independent additive risk (background risk) and (ii) the riskiness of the demand is exogenously increased. A synthetic presentation of all their findings is given in their table 1 (p. 793) and are described in Khouja (1999). Keren and Pliskin (2006) have derived a closed-form solution to the SPP problem under risk aversion but under rather restrictive restrictions, namely a uniform distribution for demand. Others have investigated the question of loss-aversion using a mean-shortfall objective function (Wang and Webster, 2008). A burgeoning literature has emerged about the interplay between the SPP and risk preferences when the decision maker has a "coherent measure of risk" (Ahmed *et al.* (2007) and Choi and Ruszczyński (2008)), namely a CVaR or a mean-absolute deviation decision rule.

In this note, we choose to remain in an expected utility framework because it appears the most used criterion for the choice under risk despite its well-known limitations. [5] Wang *et al.* (in press) discuss the impossibility of expected utility to work well with both small and large stakes. Another drawback lies in the difficulty to elicit the "true", if it exists, utility function of the decision maker (Choi and Ruszczyński, 2008). Nevertheless, expected utility remains a useful tool to derive a qualitative sensitivity analysis in very many contexts (see Gollier, 2001). It must be noted that the present analysis is only valid for expected utility because under non expected utility, the impact of a background risk can have some amazing effects in comparison with the expected utility case (see Quiggin, 2003).

It is well-known that absolute risk aversion as defined in Pratt (1964) is not sufficient *per se* to provide

[3] Even if derivatives instruments exist, it could be argued that the hedge is unadapted almost surely, at least because of the quantity risk (the number of contracts to trade is unknown *ex ante*). The remaining risk still applies multiplicatively in this case and could be considered as the MBR in our work.

[4] Apart from risk factors, Benzion *et al.* (2008) identify several other more technical factors affecting order quantity decision as the mean demand, the order-size of the maximal expected profit or the demand level of the immediately preceding round, among others.

[5] See Starmer (2000) for an exhaustive presentation.

comparative results when more than one risk are involved. Following Ross (1981), a large normative literature has emerged aiming at restricting preferences toward risk to guarantee some comparative results when several risks are considered.[6] From this literature, very few articles deal with the issue of non-additive risk.[7] Nachman (1982), Pratt (1988) and Finkelshtain *et al.* (1999) are exceptions but due to the very general form adopted for the background risk in their papers, few clear-cut conclusions are drawn.

To date, the most significant contribution about MBR is Franke, Stapleton and Schlesinger (2006) (hereafter FSS). Authors provide a number of conditions on the utility function to guarantee that the introduction of any unfair MBR, i.e. with a mean lower than unity, will lead unambiguously the decision maker to "behave more cautiously" (p 147). The motivation of the FSS' paper is that in real-life, risks rather apply multiplicatively than additively. In this case, the classical "additive" framework for decision analysis is not adapted.

The next question is then about the relevancy of introducing a MBR in the analysis of the SPP. Could a MBR really have an impact on the behavior of a newsvendor? Is the selling season not too short? To motivate our analysis, consider the case of exchange rate risk.[8] In mid-September, the U.S. dollar expressed in euro equals 0.80 against only 0.63 in the last days of July 2008. This corresponds to an increase of about 22% in a period of less than 3 months. Similar phenomenons can be observed in the USD/Yen rate evolution which has experienced variations of about 20% during July-August 1999, April-July 2002 and September-December 2008. These examples illustrate how dramatic can some changes in exchange rates be, even for currencies from developed countries. Frankel and Rose (1996) and more recently Kaminsky (2006) provide a number of similar "crashes" for emerging economies.[9] Such sharp variations in exchange rates may lead to conclude that, in some cases, the manager may have to consider the MBR and to take his decision accordingly.

The plan of the note is as follows. In the next section, we present a simple numerical example to illustrate the ambiguous impact of a MBR when the utility function is not adequately chosen. In section 3 we present the benchmark case of the SPP under risk aversion which has been studied in Eeckhoudt *et al.* (1995). We then use this case to derive our main result with MBR, provide some intuitions about the result and relevancy of the proposed conditions on the utility function. Section 3 concludes.

2 A numerical example

FSS provide a simple example emphasizing the puzzling effect of a MBR. As noted by authors, "The results for the multiplicative case do not simply mirror those of the additive case" (p. 147). We adapt their example but using a continuum of risk parameters to show that in some cases, the introduction of a MBR may well increase the participation in the risky activity. Consider first a portfolio choice

[6] This literature is excellently surveyed in Gollier (2001, chapters 8 and 9).

[7] Franke *et al.* (2006) point out that "Surprisingly, very little attention has been given to the case where the background risk is multiplicative." (p. 147)

[8] In a special section dedicated to currency crashes, Sornette (2003, p. 260) provides some examples of currency bubbles and crashes.

[9] Currencies of emerging countries are more prone to experience large movements of speculative positions, labelled "speculative attacks", from international investors. Our first examples showed that even for currencies from developed countries, large drops are likely to occur.

problem where the individual can allocate his wealth between a risk-free asset, whose return is 0.05 and a risky asset whose return is either 0.132 or 0.088 with equal probability. An additive background risk is added to this initial lottery in the form of an increase or a reduction of the final wealth of 30 with equal probability. The individual has a utility function of the hyperbolic absolute risk aversion (HARA) form such that $u(z) = -\frac{1}{2}\left(\eta + z\right)^{-2}$. The constant η is chosen such that $\eta + z$ always remains positive for wealth levels of interest.

Figure 1 illustrates the proportion of risky asset for $\eta \in [-50, 50]$ and an initial wealth $w_0 = 100$. The solid line is the initial choice, i.e. without background risk. The dotted line is the proportion of risky asset under the additive background risk. As is well-known, the individual invests less in the risky asset when confronted with an (unfair) additive background risk when its preferences satisfy risk vulnerability (Gollier and Pratt, 1996). The chosen utility function $u(z) = -\frac{1}{2}\left(\eta + z\right)^{-2}$ satisfies risk vulnerability conditions as given by Gollier and Pratt (1996) because it exhibits decreasing absolute risk aversion (DARA) and decreasing absolute prudence (DAP). These two conditions in tandem characterize standardness as defined by Kimball (1993) which is a sufficient condition for risk vulnerability.[10] Now consider a MBR such that final wealth can be multiplied by a factor either 0.7 or 1.3 with equal probability. The dashed line of figure 1 represents the risky asset proportion under MBR. Indeed, for some values of the parameter η in the range considered, the optimal level of investment in the risky asset is increased. This is a rather counterintuitive result which is due to the properties of the utility function considered here and the particular effect of the MBR in opposition with the additive one.

[Figure 1 about here]

As a second example, consider the same utility function, but now in the SPP framework. Utility function remains the same and we set, as in Eeckhoudt *et al.* (1995), salvage value at zero, unit selling price at 28, unit cost at 20 and demand equalling zero with probability 0.25 or 100 with probability 0.75. For calibration purpose, the initial wealth is fixed at $w_0 = 425$, which guarantees the positivity of $\eta + z$. The solid line of the figure 2 represents the optimal order without background risk. An additive background risk (+80 or −80 with equal probability on the final wealth) is added and is plotted with the dotted line. Again, optimal order is always reduced. We then consider the same MBR as in the portfolio problem example above. The dashed line, which represents the optimal order, shows that the optimal order is *increased* under MBR. This conclusion is robust to various values for the risk parameter η and again emphasizes the kind of counterintuitive results which could be encountered when considering MBR.

[Figure 2 about here]

These examples claim for a deeper qualitative analysis of the optimal order under MBR, at least to guarantee that any unfair risk which would apply multiplicatively to the final wealth would lead to a decrease in the optimal order. As we will see, conditions developed in the next section to warrant a decreased optimal order are not met by the utility function of the HARA class considered in these examples.

[10] For a given level of wealth w and a utility function u, absolute risk aversion is defined as: $A_u(w) = -u''(w)/u'(w)$ and absolute prudence as: $P_u(w) = -u'''(w)/u''(w)$. For more details, see Gollier (2001).

3 Model and main result

We consider a standard single-period problem (SPP). The newsvendor orders q products (q continuous) at a unit price c from a supplier and sells these products at a unit price $p > c$. Demand Δ is a nonnegative random variable with cumulative distribution function (cdf) $G(\delta)$ on a support $[0, B]$ with B finite. A particular realization of demand is denoted δ to distinguish it from the random variable Δ. If realized demand δ is lower than q, then the unsold goods are salvages at a unit price $s < c$. We set the initial wealth at zero so that the variable of interest will be the profit in place of the final wealth.[11] The profit of the decision maker for a given δ is given by:

$$\pi(q, \delta) = p\delta - cq + s(\max[0, q - \delta]) \tag{1}$$

To keep things as simple as possible and concentrate our attention on the impact of the MBR, without modifying qualitative results, we do not introduce any shortage cost penalty or repurchase cost. Note that these shortcomings have actually no consequence because our aim is not to derive any comparative statics results.[12] Because the payoff function is piecewise linear, it is convenient to partition this function along this natural decomposition. Again for δ, a given realization of Δ, the profit function can be expressed as follows:

$$\pi(q, \delta) = \begin{cases} \pi_-(q, \delta) = (p - s)\delta - (c - s)q & \text{if } \delta < q \\ \pi_+(q, \delta) = (p - c)q & \text{if } \delta \geq q \end{cases}$$

3.1 Newsboy problem under risk aversion: the benchmark case

We consider a newsvendor with risk preferences described by a utility function $u(.)$, nondecreasing and concave. $u(.)$ is assumed to be continuous differentiable at an order sufficient to define the second derivative of absolute and relative risk aversions.[13] The newsvendor faces the problem of determining an optimal order quantity q^* so that his expected utility is maximized or:

$$q^* \in \arg\max_{q \in \mathbb{R}_+} \; V(q) \equiv Eu[\pi(q, \Delta)] \tag{2}$$

with the following expression of the expected utility for a quantity q:

$$V(q) = \int_0^q u[\pi_-(q, \delta)]dG(\delta) + \int_q^B u[\pi_+(q, \delta)]dG(\delta) \tag{3}$$

The first-order condition (FOC) is given by:

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[11] At this point, we could note that the initial wealth may be random resulting in a model à la Kihlstrom *et al.* (1981) and Nachman (1982). Conjunction of an additive background risk with a multiplicative one being not an issue in this paper, we only consider the certain initial wealth case. For a discussion of simultaneous presence of both kinds of risks, eventually correlated, see Tsetlin and Winkler (2005).

[12] Comparative statics results under some different attitudes toward risk are provided in Eeckhoudt *et al.* (1995). A very interesting and recent result is given in Wang *et al.* (2008) who highlight the ambiguous effect of an increase in selling price on the optimal order in an expected utility framework using the Rabin's (2000) "Calibration Theorem".

[13] Relative risk aversion is defined such as: $R_u(w) = -wA_u = -wu''(w)/u'(w)$. We thus assume that u is sufficiently smooth so as $A''_u(.)$ and $R''_u(.)$ are well defined.

$$V'(q)\Big|_{q=q^*} = (s-c)\int_0^{q^*} u'[\pi_-(q,\delta)]dG(\delta) + (p-c)\int_{q^*}^{B} u'[\pi_+(q,\delta)]dG(\delta) = 0 \tag{4}$$

and guarantees a unique solution for a maximum because $V(q)$ is concave in q. In this framework, we can easily reconsider the well-established "quantile result" under risk neutrality[14] by taking $u(.)$ linear such as $u'(.) = L$, with L a positive scalar. In this case, condition 4 is rewritten:

$$V_n'(q)\Big|_{q=q_n^*} = (s-c)\int_0^{q_n^*} LdG(\delta) + (p-c)\int_{q_n^*}^{B} LdG(\delta) = 0 \tag{5}$$

where $V_n'(q)$ stands for the FOC under risk neutrality. After straightforward manipulation, we obtain: $q_n^* = G^{-1}\left(\frac{p-c}{p-s}\right)$.

Under expected utility and assuming risk aversion, the optimal order quantity is reduced (see Lau (1980) or Eeckhoudt *et al.* (1995)). This follows by noting that for $\delta_0 < q_n^*$, $\pi_-(q_n^*, \delta_0) < \pi_-(q_n^*, q_n^*)$, implying an increase of the integrand (marginal utility) of the first term of the right-hand-side (RHS) term under risk aversion. The inverse being true for the case $\delta_0' > q_n^*$, the integrand of the second term of the RHS is reduced. Because by hypothesis $s - c < 0$ and $p - c > 0$, the evaluation of condition (4) at q_n^* yields the following result:

$$V'(q)\Big|_{q=q_n^*} < u'[\pi(q_n^*, q_n^*)] \times V_n'(q)\Big|_{q=q_n^*} \tag{6}$$

$$< 0 \tag{7}$$

This inequality implies $q^* < q_n^*$ due to the concavity of the problem in q.

3.2 The introduction of a multiplicative background risk

Now consider the newsvendor faces a MBR, denoted ε, independent from the stochastic demand Δ whose support is $[\underline{a}, \overline{a}]$ with $\underline{a} < 0$ and expectation equals unity. In this sense, ε can be thought as a neutral (discrete or continuous) multiplicative lottery. This form of market incompleteness may arise for instance when the newsvendor is exposed to an exchange rate risk or an inflation risk and no perfect hedging instrument is available.

The newsvendor still wishes to maximize the expected utility of his profit or choose :

$$q_b^* \in \arg\max_{q\in\mathbb{R}_+} \; V(q,\varepsilon) \equiv Eu[\varepsilon.\pi(q,\Delta)] \tag{8}$$

The function $V(q,\varepsilon)$ can be written using the independence between demand and MBR as the following iterated integral:

$$V(q,\varepsilon) = \int_0^{B}\int_{\underline{a}}^{\overline{a}} u[\epsilon.\pi(q,\Delta)]\,dF(\epsilon)\,dG(\delta) \tag{9}$$

[14] This property can be derived using the Leibniz rule or, more originally, the expression of profit's moments as in Lau (1980).

As is common in the background risk literature, we introduce the derived utility function (see Kihlstrom *et al.* (1981) and Nachman (1982)) whose properties will be of interest to determine the optimal level of the decision variable. Let us note $v(\pi(q,\delta))$ the expectation on the support $[\underline{a},\overline{a}]$ of the initial utility function $u(.)$ evaluated at a given q and a given realized demand δ:

$$v(\pi(q,\delta)) \equiv \int_{\underline{a}}^{\overline{a}} u[\epsilon.\pi(q,\delta)]\, dF(\epsilon) \tag{10}$$

where ϵ is a realization of ε. Using this derived utility function, it is possible to express the FOC of the maximization program under MBR as:

$$V'(q,\varepsilon)\Big|_{q=q_b^*} = (s-c)\int_0^{q_b^*} v'[\pi_-(q,\delta)]\, dG(\delta) + (p-c)\int_{q_b^*}^{B} v'[\pi_+(q,\delta)]\, dG(\delta) = 0 \tag{11}$$

Under "multiplicative risk vulerability" (FSS, Main theorem), $v(.)$ is uniformly more risk averse than $u(.)$. Since Pratt (1964, Theorem 1, p.128), we know that decision maker with utility $v(.)$ is more risk averse than decision maker with utility $u(.)$ if and only if $v[u^{-1}(.)]$ is a concave function or in a more intuitive manner $v(.) = \phi[u(.)]$ with $\phi(.)$ an increasing and concave function. Thus, condition (11) can be rewritten:

$$V'(q,\varepsilon)\Big|_{q=q_b^*} = (s-c)\int_0^{q_b^*} \phi'(u[\pi_-(q,\delta)])u'[\pi_-(q,\delta)]\, dG(\delta) + (p-c)\int_{q_b^*}^{B} \phi'(u[\pi_+(q,\delta)])u'[\pi_+(q,\delta)]\, dG(\delta) \tag{12}$$

Then, evaluating this condition at q^* (the optimal order with risk aversion but without MBR) as in Eeckhoudt *et al.* (1995) and resorting to the same reasoning as for condition (6) leads to:

$$V'(q,\varepsilon)\Big|_{q=q^*} < \phi'(u[\pi(q^*,q^*)]) \times V'(q)\Big|_{q=q^*} \tag{13}$$

$$< 0 \tag{14}$$

Using this last result and Main theorem in FSS, we can now state our principal result.

Proposition 1 *In the newsvendor problem, the optimal order quantity is decreased under a multiplicative neutral background risk when preferences are multiplicatively risk vulnerable.*

Because multiplicative risk vulnerability is difficultly defined (see eq. (5) in FSS), we rely on part (ii) of their corollary 1 to state another, but weaker, sufficient condition for our problem.

Corollary 1 *In the newsvendor problem, the optimal order quantity will decrease in response to the introduction of a multiplicative neutral background risk if relative risk aversion is increasing, convex and always higher than unity.*

The story behind this result is that by decreasing its optimal order, the newsvendor has an impact on the distribution of its future wealth. Because of the complexity of the sufficient condition, we cannot describe with precision the exact phenomenon leading to a decrease in the optimal order. Nevertheless, as is common when concepts such as prudence and temperance are at work (see Gollier and Pratt (1996) and Gollier (2001) for a definition and a discussion of these concepts), the individual may want to reduce the probability of occurrence of extremely bad outcomes. By reducing its optimal order, the newsvendor thus limits its maximum profit, but it also removes the possibility of the conjunction of two bad realizations, namely a low demand and a unfavorable, say, exchange rate. As noted above, this choice is made at the cost that profit is limited, but this is the usual trade-off encountered in risk management.[15]

At first sight, it may appear that these conditions on the utility function are very restrictive. As a matter of fact, they seem to be met in a number of economic or financial studies and their simultaneous presence is very plausible. First, the hypothesis of increasing relative risk aversion is supported in the recent paper by Guiso and Paiella (2008) which is based on a large survey designed by the Bank of Italy to elicit risk preferences of households.[16] Meyer and Meyer (2005) also discuss the issue of relative risk aversion and its first derivative. Evidence of the convexity of the relative risk aversion function may be found in Bliss and Panigirtzoglou (2004) (and references therein) who use option data. It must be noted that in this case, it is the market degree of risk aversion which is estimated, thereby creating some "representative agent" estimation problems. Finally, relative risk aversion is generally found to be higher than one in empirical works (see table VII in Bliss and Panigirtzoglou (p. 432) for estimates in previous studies dating back to 70s). At a more theoretical level, relative risk aversion should also be higher than unity as recently shown in Eeckhoudt *et al.* (2008).

A natural question is whether commonly used utility functions satisfy the sufficient conditions expressed above. FSS discuss this issue at length at the end of their section 3. We refer the reader to their paper to learn more about the relation between common utility functions and multiplicative risk vulnerability. Nevertheless, we can note that utility functions of the HARA class are not in general multiplicatively risk vulnerable, but some of them, commonly used in financial literature, as the CRRA functions, are multiplicatively risk vulnerable in the weak sense.[17]

4 Concluding remarks

This note showed under which conditions the introduction of a MBR unambiguously leads to a lower order in the SPP. These conditions are not intuitive due to their complexity, but allow to put some bounds on forms of utility to retain in numerical applications. Until now, no such condition, even in a more restrictive framework, has been provided in the literature. The importance of this result lies in the fact that situations where risks apply multiplicatively are common, perhaps more common than cases where they apply additively.

In the present work, we did not examine the impact of an increase in the MBR because this may lead

[15] This is particularly true, for instance, in the case of the optimal hedging policy whose aim is to reduce variance in profit, but whose first consequence is to reduce the range of attainable profits.

[16] The working paper version of this article (Guiso and Paiella, 2001) is cited in FSS, who also argue that evidence of the contrary may be found in Ogaki and Zhang (2001).

[17] Derivation at the second order of the general HARA utility function straightforwardly shows that multiplicative risk vulnerability property depends on the value of the parameter η. For positive value of η, the introduction of a MBR leads to a less cautious behavior, thus explaining our results in the numerical example section. The "weak sense" means that the introduction of a MBR may have no effect on the behavior of the decision maker as is the case for CRRA utility functions.

to counterintuitive results as in Ridder *et al.* (1998) or conditions difficult to interpret as in Eeckhoudt *et al.* (1995). Nevertheless, it would be of interest to determine, at least in a parametric setting, the impact of an increase in the MBR (second moment or higher order moments) on the optimal order of our newsboy. This is left for future research.

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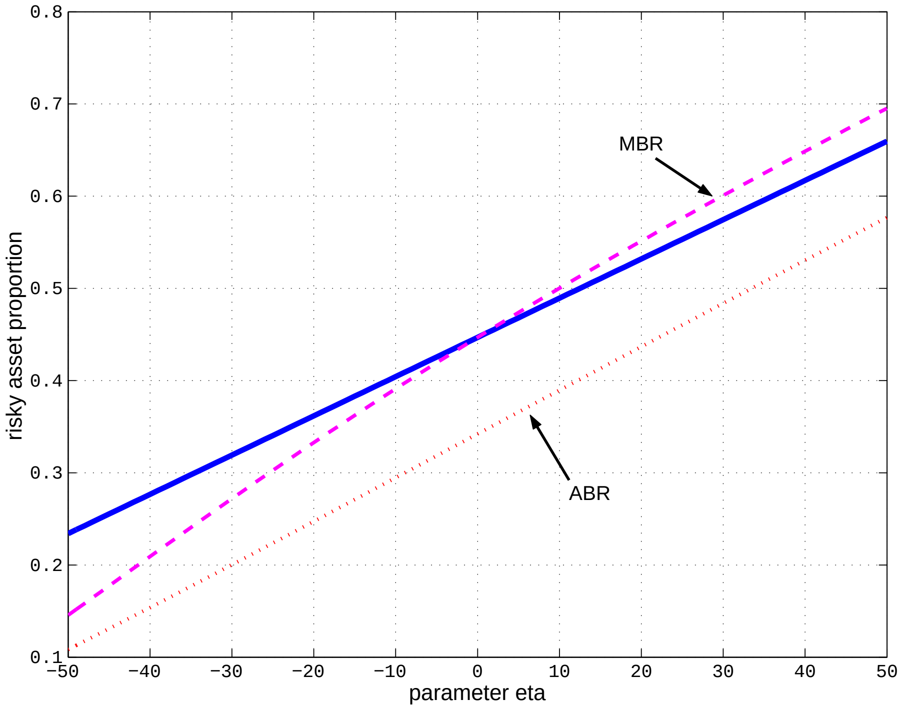

Figure 1: Risky asset proportions for the portfolio choice model. Solid line [dotted line] [dashed line] represents the case without [with additive, ABR][with multiplicative, MBR] background risk.

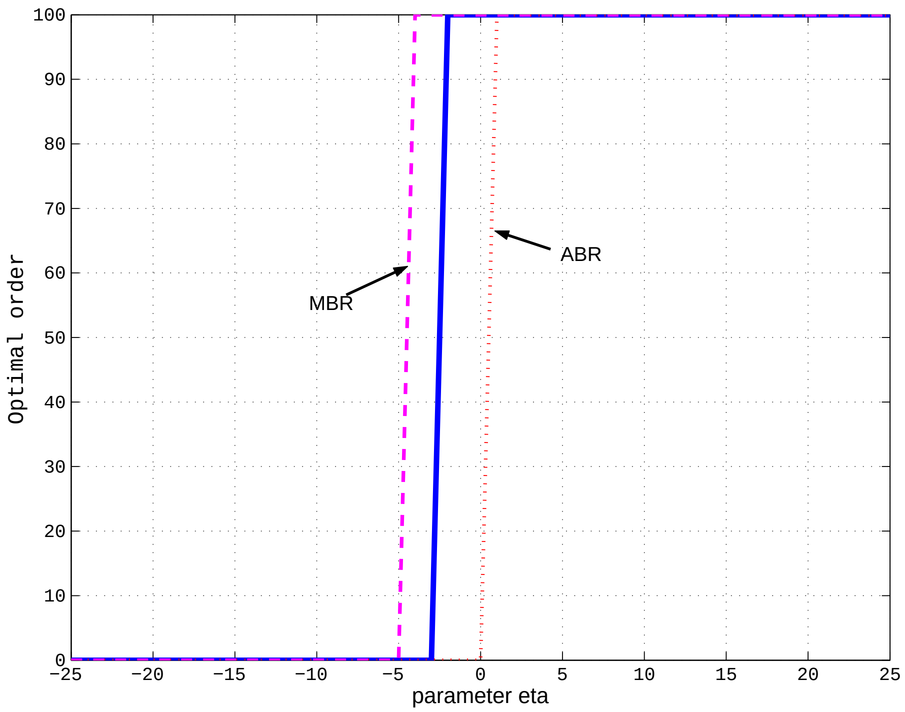

Figure 2: Optimal order for the newsvendor problem. Solid line [dotted line] [dashed line] represents the case without [with additive, ABR][with multiplicative, MBR] background risk.

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