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Forward Indifference Valuation of American Options*

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Abstract

We analyze the valuation of American options under the forward performance criterion introduced by Musiela and Zariphopoulou (2008). In this framework, the performance criterion evolves forward in time without reference to a specific future time horizon, and may depend on the stochastic market conditions. We examine two applications: the valuation of American options with stochastic volatility and the modeling of early exercises of American-style employee stock options. We also study the marginal forward performance price, which is related to the classical marginal utility price introduced by Davis (1997). Among others, we find that, under arbitrary time-monotone forward performance criteria, the marginal forward indifference price for any claim is always independent of the investor's wealth, and is represented as the expected discounted payoff under the minimal martingale measure.

1 Introduction

Utility maximization theory has been central to quantifying rational investment decisions and risk-averse valuations of assets at least since the work of von Neumann and Morgenstern in the 1940s. In the Merton (1969) problem of continuous-time portfolio optimization, utility is defined at some fixed time horizon in the future when investment decisions are assessed in terms of the expected utility of terminal wealth. For portfolios involving derivatives and associated utility indifference pricing problems, derivative payoffs or random endowments may be realized at random times, which requires the specification of utility at other times, not just at a single terminal time. This consideration is particularly important for investment and pricing problems involving defaultable securities or American options.

One way to address this issue is to consider the definition of utility at the time of a random cash flow as analogous to specifying what the investor does with the endowment thereafter. Any answer to the latter question necessarily involves details of the market in which he might invest, and utilities and markets are inextricably linked. Some examples of works based on this idea include, among others, Oberman and Zariphopoulou (2003), Leung and Sircar (2009a) for utility indifference pricing of American options, and Leung et al. (2008) and Jaimungal and Sigloch (2010) for defaultable securities. This approach allows for comparing utilities of

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wealth at different times. However, as is common in classical utility indifference pricing, the investor's risk preferences at intermediate times and the optimal investment decisions still directly depend on an *a priori* chosen investment horizon.

This issue of horizon dependence has been addressed by one of the authors and Musiela through the construction of the forward performance criterion (see, for example, Musiela and Zariphopoulou (2008)). In this approach, the investor's utility is specified at an initial time, and his risk preferences at subsequent times evolve forward without reference to any specific ultimate time horizon. This results in a stochastic utility process, called the *forward performance process*, whose evolution depends on the random market conditions. In a related study, Henderson and Hobson (2007) analyzed the optimal timing of asset sale based on the so-called horizon-unbiased utility functions which have no preferred horizon for the associated dynamic portfolio optimization problem. Hence, these approaches necessarily connect risk preferences with market models. The risk profile of a given investor is no longer considered separately from his investment opportunities and the market. This is entirely natural: the current economic crisis has clearly shown increased risk aversion in investors as the market has fallen.

In this paper, we develop an indifference valuation methodology based on the forward performance criterion. Specifically, we study the valuation of a long position in an American option in an incomplete diffusion market model. Our main objective is to analyze the optimal trading and exercise strategies that maximize the option holder's forward performance coming from both the dynamic portfolio and the option payoff upon exercise. In Section 2, we formulate the combined stochastic control and optimal stopping problem faced by the option holder. Then, we define the holder's *forward indifference price* for the American option by comparing the optimal expected forward performance with and without the derivative (see Definition 2). The analysis of the indifference price will yield a number of useful mathematical characterizations and financial interpretations for optimal trading and exercise strategies.

In Section 3, we discuss the exponential forward indifference valuation of an American option in a stochastic volatility model. Using the analytical properties of the exponential forward performance, we show that the forward indifference price is wealth-independent, and we derive its associated variational inequality as well as its dual representation. We also provide a comparative analysis between the forward and classical exponential indifference prices. For instance, we show that the forward indifference price representation involves a relative entropy minimization (up to a stopping time) with respect to the minimal martingale measure (MMM), as opposed to the minimal entropy martingale measure (MEMM) that arises in the classical exponential utility indifference price (see, among others, Rouge and El Karoui (2000) and Delbaen et al. (2002) for European claims, and Leung and Sircar (2009b) for American claims). We also present this contrasting difference in the asymptotic results of indifference prices.

Another application studied in this paper is the modeling of early exercises of employee stock options (ESOs), which are American-style call options written on the firm's stock granted to the employee as a form of compensation. In Section 4, we assume a forward performance criterion for the employee and investigate the impacts of various factors, such as wealth and risk tolerance function, on the employee's exercise timing. In particular, we find that the employee tends to exercise the ESO earlier when his wealth approaches zero.

Lastly, in Section 5, we introduce an alternative valuation mechanism for American options based on the *marginal* forward performance. In the classical utility framework, as introduced by Davis (1997), the *marginal utility price* represents the per-unit price that a risk-averse investor is willing to pay for an infinitesimal position in a contingent claim. In general, the marginal utility price is closely linked to both the investor's utility function and the market

setup, and it only becomes wealth independent under very special circumstances (see Kramkov and Sirbu (2006) for details). We adapt the classical definition to our forward performance framework and give a definition of the *marginal forward indifference price*. We show that, in contrast to the classical marginal utility price, the marginal forward indifference price under time monotone criteria turns out to be independent of both the holder's wealth and the forward performance criterion, and is equivalent to pricing under the *minimal martingale measure*. Section 6 concludes the paper and discusses extensions for future research.

2 Forward Investment Performance Measurement and Indifference Valuation

We fix a filtered probability space $(\Omega, \mathcal{F}, \mathbb{P})$, with a filtration $(\mathcal{F}_t)_{t \geq 0}$ that satisfies the usual conditions of right continuity and completeness. In addition, all stochastic processes considered in this paper are continuous-path processes. The financial market consists of two liquidly traded assets, namely, a riskless money market account and a stock. The money market account has the price process B that satisfies

$$dB_t = r_t B_t dt, \quad (1)$$

with $B_0 = 1$, where $(r_t)_{t \geq 0}$ is a non-negative \mathcal{F}_t -adapted interest rate process. We shall use B as the numeraire throughout.

The discounted stock price S is modeled as a continuous Itô process satisfying

$$dS_t = S_t \sigma_t (\lambda_t dt + dW_t), \quad (2)$$

with $S_0 > 0$, where $(W_t)_{t \geq 0}$ is an \mathcal{F}_t -adapted standard Brownian motion. The Sharpe ratio $(\lambda_t)_{t \geq 0}$ is a bounded \mathcal{F}_t -adapted process, and the volatility coefficient $(\sigma_t)_{t \geq 0}$ is strictly positive bounded \mathcal{F}_t -adapted process. Moreover, we assume that a strong solution exists for the SDE (2).

Starting with initial endowment $x \in \mathbb{R}$, the investor dynamically rebalances his portfolio allocations between the stock and the money market account. Under the self-financing trading condition, the discounted wealth satisfies

$$dX_t^\pi = \pi_t \sigma_t (\lambda_t dt + dW_t), \quad (3)$$

where $(\pi_t)_{t \geq 0}$ represents the discounted cash amount invested in stock. The set of admissible strategies \mathcal{Z} consists of all self-financing \mathcal{F}_t -adapted processes $(\pi_t)_{t \geq 0}$ such that $\mathbb{E}\{\int_0^s \sigma_t^2 \pi_t^2 dt\} < \infty$ for each $s > 0$. For $0 \leq t \leq s$, we denote by $\mathcal{Z}_{t,s}$ the set of admissible strategies over the period $[t, s]$.

In the standard Merton portfolio optimization problem, risk preferences are modeled by a deterministic utility function $\hat{U}(\cdot)$ defined at some fixed terminal time T . Starting with \mathcal{F}_t -measurable wealth X_t at time $t \leq T$, the Merton value process is given by

$$M_t(X_t) = \operatorname{ess\,sup}_{\pi \in \mathcal{Z}_{t,T}} \mathbb{E} \left\{ \hat{U}(X_T^\pi) \mid \mathcal{F}_t \right\}. \quad (4)$$

When the *dynamic programming principle* holds, the Merton problem can be written as

$$M_t(X_t) = \operatorname{ess\,sup}_{\pi \in \mathcal{Z}_{t,s}} \mathbb{E} \{ M_s(X_s^\pi) \mid \mathcal{F}_t \}, \quad 0 \leq t \leq s \leq T. \quad (5)$$

Some well-known examples when (5) holds include i) markets with Markovian dynamics where the optimal portfolio allocation can be found by solving a Hamilton-Jacobi-Bellman (HJB)

equation; ii) when the utility is of exponential type, in which case (5) holds under quite general semimartingale models (see Mania and Schweizer (2005); Leung and Sircar (2009b)); and iii) when expected utility is replaced by a dynamic time-consistent concave utility functional, defined, for instance, from a BSDE in Itô markets (see Klöppel and Schweizer (2006); Cheridito and Kupper (2009)). The dynamic programming principle (5) is taken as the *defining characteristic* of the forward performance criterion.

In the forward performance framework, the investor's utility function $u_0(x)$ is defined at the initial time 0, and his performance criterion evolves forward in time. We adapt the definition of the forward performance process given by Musiela and Zariphopoulou (2008):

Definition 1 *An \mathcal{F}_t -adapted process $(U_t(x))_{t \geq 0}$ is a forward performance process if:*

1. *it satisfies the initial datum $U_0(x) = u_0(x)$, $x \in \mathbb{R}$, where $u_0 : \mathbb{R} \mapsto \mathbb{R}$ is an increasing and strictly concave function of x ,*
2. *for each $t \geq 0$, the mapping $x \mapsto U_t(x)$ is increasing and strictly concave in $x \in \mathbb{R}$, and*
3. *for $0 \leq t \leq s < \infty$, we have*

$$U_t(X_t) = \operatorname{ess\,sup}_{\pi \in \mathcal{Z}_{t,s}} \mathbb{E}\{U_s(X_s^\pi) | \mathcal{F}_t\}, \quad (6)$$

for any \mathcal{F}_t -measurable initial wealth X_t .

In related studies, condition 3 is also referred to as the horizon-unbiased condition in Henderson and Hobson (2007) and the self-generating condition in Žitković (2009).

As with the classical utility maximization problem, the existence and characterization of the optimal strategy in `eqrefUtx-mtg` are challenging questions and depend on the market structure and utility function used. Related research for forward performance processes includes Musiela and Zariphopoulou (2010b), El Karoui and M'Rad (2010), and Žitković (2009) (for exponential preferences). In this paper, however, our analysis will focus on a class of *explicit* forward performance processes (see Theorem 3), whose optimal strategies have been completely characterized in the recent papers Berrier et al. (2009) and Musiela and Zariphopoulou (2010a). Our objective is to apply forward performance to the indifference pricing of American options, and investigate some properties of the forward indifference prices.

2.1 Forward Indifference Price

We introduce the forward indifference valuation from the perspective of the holder of an American option. The option payoff is modelled by an \mathcal{F}_t -adapted bounded process denoted by $(g_t)_{0 \leq t \leq T}$, with a finite expiration date T . The collection of admissible exercise times is the set of stopping times with respect to $\mathcal{F}_{0,T} = (\mathcal{F}_t)_{0 \leq t \leq T}$ that take values in $[0, T]$. For $0 \leq t \leq s \leq T$, we denote by $\mathcal{T}_{t,s}$ the set of stopping times taking values in $[t, s]$.

The option holder chooses his dynamic trading strategy π and exercise time τ , so as to maximize his expected forward performance from both investing in the market and receiving the option payoff. This leads to a combined stochastic control and optimal stopping problem. Specifically, we define

$$V_t(X_t) = \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,sup}_{\pi \in \mathcal{Z}_{t,\tau}} \mathbb{E}\{U_\tau(X_\tau^\pi + g_\tau) | \mathcal{F}_t\}, \quad t \in [0, T], \quad (7)$$

which is the holder's value process based on a forward performance starting at time t with wealth X_t .

In the classical case with a terminal utility function \hat{U} , the holder's optimal investment problem is to solve

$$\operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,sup}_{\pi \in \mathcal{Z}_{t,\tau}} \mathbb{E} \{M_\tau(X_\tau^\pi + g_\tau) \mid \mathcal{F}_t\},$$

where M is the solution to the Merton problem defined in (4). In this formulation, M plays the role of intermediate utility at the stopping times $\tau \leq T$, and corresponds to specifying that option proceeds received at any exercise time τ are re-invested following the Merton optimal strategy up till time T . By contrast, the forward performance process U specifies utilities at all times, without reference to any specific horizon.

The holder's forward indifference price p_t for the American option g is defined as the discounted cash amount such that the option holder is indifferent between two positions: optimal investment with an American option position, and optimal investment without the American option but instead with extra initial wealth p_t .

Definition 2 *The holder's forward indifference price process $(p_t)_{0 \leq t \leq T}$ for the American option is defined by the equation*

$$V_t(X_t) = U_t(X_t + p_t), \quad t \in [0, T], \quad (8)$$

where V_t and U_t are given in (7) and (6) respectively.

The forward indifference price is useful for characterizing the option holder's optimal exercise time τ^* . Under appropriate integrability conditions (Karatzas and Shreve, 1998, Theorem D.12), the optimal stopping time is the first time the value process reaches the reward process. From (7) and (8), we have

$$\begin{aligned} \tau_t^* &= \inf \{t \leq s \leq T : V_s(X_s) = U_s(X_s + g_s)\} \\ &= \inf \{t \leq s \leq T : U_s(X_s + p_s) = U_s(X_s + g_s)\} \\ &= \inf \{t \leq s \leq T : p_s = g_s\}. \end{aligned} \quad (9)$$

The representation (9) implies that the option holder will exercise the American option as soon as the forward indifference price reaches (from above) the option payoff. It allows us to analyze the holder's optimal exercise policy through his forward indifference price.

In Sections 3 and 4, we will focus our study on two specific financial applications: i) the valuation of an American option written on a stock S with stochastic volatility under forward performance criterion of *exponential* type (to be defined in (26)), and ii) modeling early exercises of employee stock options (ESOs) for criteria beyond the exponential forward performance.

2.2 Forward Performance of Generalized CARA/CRRA Type

Henceforth, we will focus our attention on a special class of forward performance processes introduced by Musiela and Zariphopoulou (2008), namely, the time-monotone ones. These processes are represented by the compilation of a deterministic function $u(x, t)$ which models the investor's dynamic risk preferences, and a stochastic time-change $(A_t)_{t \geq 0}$ that solely depends on the market. Recently, Berrier et al. (2009) and Musiela and Zariphopoulou (2010a) studied various properties and alternative characterizations of this family of forward performances.

Theorem 3 (Musiela and Zariphopoulou (2008) and (2010)) Define the stochastic process

$$A_t = \int_0^t \lambda_s^2 ds, \quad t \geq 0. \quad (10)$$

Suppose $u : \mathbb{R} \times \mathbb{R}_+ \mapsto \mathbb{R}$ is $\mathcal{C}^{3,1}$, strictly concave, increasing in its spatial argument, and satisfies the nonlinear partial differential equation

$$u_t = \frac{1}{2} \frac{u_x^2}{u_{xx}}, \quad (11)$$

with initial condition $u(x, 0) = u_0(x)$, where $u_0 \in \mathcal{C}^3(\mathbb{R})$. Then, the process $U_t(x)$, defined by

$$U_t(x) = u(x, A_t), \quad t \geq 0, \quad (12)$$

is a forward performance process. Moreover, the trading strategy π^* given by

$$\pi_t^* = -\frac{\lambda_t}{\sigma_t} \frac{u_x(X_t^*, A_t)}{u_{xx}(X_t^*, A_t)}, \quad t \geq 0, \quad (13)$$

where $X^* = X^{\pi^*}$ is the associated wealth process following (3), is optimal.

By its definition in (10), A is an increasing stochastic process that depends on the Sharpe ratio of the traded asset S . Also, it is commonly called the *mean-variance trade-off* process (see e.g. Pham et al. (1998) and references therein). In constructing the forward performance process in (12), A acts as a stochastic time change to the deterministic preference function $u(x, t)$.

We stress that because problem (11) is ill-posed, one needs to specify in detail the class of initial conditions that yields a well-defined solution for all times. This is not a trivial matter, and was investigated in detail in Musiela and Zariphopoulou (2010a). A related problem, that was also studied there, is to determine for which initial conditions the policies specified by (13) are admissible. Because the related arguments for both the aforementioned questions are quite lengthy, we provide the key results in the Appendix. The time-monotone forward performance criteria used in Section 3 and 4 belong to the admissible class.

A quantity that plays a crucial role in the description of the optimal wealth and portfolio processes (X^*, π^*) is the so-called *local risk tolerance* function $R : \mathbb{R} \times \mathbb{R}_+ \mapsto \mathbb{R}_+$, defined by

$$R(x, t) = -\frac{u_x(x, t)}{u_{xx}(x, t)}, \quad (14)$$

with u solving (11). Using (13) and (14), the dynamics of the optimal wealth X^* can be expressed as

$$dX_t^* = R(X_t^*, A_t) \lambda_t (\lambda_t dt + dW_t). \quad (15)$$

Furthermore, by applying differentiation to (14), one can show that R is the solution of an equation of fast diffusion type, namely

$$R_t + \frac{1}{2} R^2 R_{xx} = 0. \quad (16)$$

The above *autonomous* equation for $R(x, t)$ suggests that one could first model the local risk tolerance directly, and in turn recover the dynamic risk preference function $u(x, t)$ from (14). This provides an alternative way to construct forward performance criteria. This idea

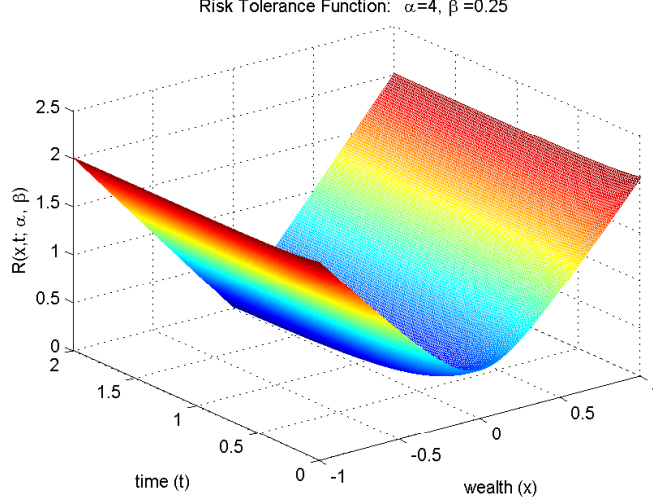


Figure 1: The risk tolerance function $R(x, t; \alpha, \beta)$ in (17) with $\alpha = 4$, and $\beta = 0.25$. For any fixed wealth x , $R(x, \cdot; \alpha, \beta)$ decreases with time, while for any fixed time t , $R(\cdot, t; \alpha, \beta)$ increases as wealth decreases or increases away from zero.

was further developed in Zariphopoulou and Zhou (2008) who proposed the following two-parameter family of risk tolerance functions:

$$R(x, t; \alpha, \beta) := \sqrt{\alpha x^2 + \beta e^{-\alpha t}}, \quad x \in \mathbb{R}, t \geq 0, \alpha, \beta > 0. \quad (17)$$

We illustrate an example of this risk tolerance in Figure 1.

There are several reasons to work with this family of risk tolerance. First, it yields, in the limits as α or β goes to zero, the risk tolerance functions that resemble those related to the three most popular cases, specifically, the *exponential*, *power* and *logarithmic*. We summarize from Zariphopoulou and Zhou (2008) the limiting cases leading to risk tolerance functions and the corresponding utilities as follows:

$$\lim_{\alpha \rightarrow 0} R(x, t; \alpha, \beta) = \sqrt{\beta}, \quad u(x, t) = -e^{-\frac{x}{\sqrt{\beta}} + \frac{t}{2}}, \quad x \in \mathbb{R} \quad (\text{exponential}); \quad (18)$$

$$\lim_{\beta \rightarrow 0} R(x, t; \alpha, \beta) = \sqrt{\alpha} x, \quad u(x, t) = \frac{x^\delta}{\delta} e^{-\frac{\delta}{2(1-\delta)} t}, \quad x \geq 0, \alpha \neq 1 \quad (\text{power}); \quad (19)$$

$$\lim_{\beta \rightarrow 0} R(x, t; 1, \beta) = x, \quad u(x, t) = \log x - \frac{t}{2}, \quad x > 0 \quad (\text{logarithmic}), \quad (20)$$

where $\delta := \frac{\sqrt{\alpha}-1}{\sqrt{\alpha}}$. According to (19) and (20), in the limit $\beta \downarrow 0$, $R(x, t; \alpha, \beta)$ is defined only over a positive/strictly positive wealth domain. In Figure 2, we illustrate the limit in (18) where the risk tolerance function converges to the constant $\sqrt{\beta}$ as $\alpha \downarrow 0$. In Section 3, we will work with the exponential forward performance which corresponds to constant risk tolerance in (18). In view of the limits in (18) and (19), we may call $\sqrt{\alpha}$ the *power risk tolerance* and $\sqrt{\beta}$ the *exponential risk tolerance*. Hence, the risk tolerance $R(x, t; \alpha, \beta)$ for $\alpha, \beta > 0$ can be viewed as a combination/interpolation of the power and exponential extremes.

For the general case with $\alpha, \beta > 0$, Zariphopoulou and Zhou (2008) compute, via integration of (14), the dynamic risk preference function $u(x, t; \alpha, \beta)$ associated with $R(x, t; \alpha, \beta)$ in (17):

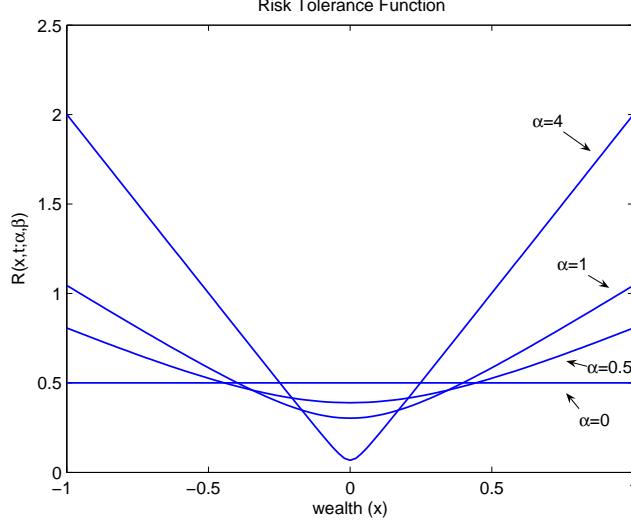


Figure 2: As α decreases from 4 to 0, with $\beta = 0.25$ and $t = 1$, the risk tolerance function $R(x, t; \alpha, \beta)$ converges to the constant level $\sqrt{\beta} = 0.5$, as predicted by the limit in (18).

Proposition 4 (Proposition 3.2 of Zariphopoulou and Zhou (2008)) The dynamic risk preference function $u(x, t; \alpha, \beta)$ associated with $R(x, t; \alpha, \beta)$ in (17) for $\alpha, \beta > 0$ is given by

$$u(x, t; \alpha, \beta) = m \frac{\kappa^{1+\frac{1}{\kappa}}}{\alpha - 1} e^{\frac{1-\kappa}{2}t} \frac{\frac{\beta}{\kappa} e^{-\alpha t} + (1 + \kappa)x(\kappa x + \sqrt{\alpha x^2 + \beta e^{-\alpha t}})}{(\kappa x + \sqrt{\alpha x^2 + \beta e^{-\alpha t}})^{1+\frac{1}{\kappa}}} + n, \quad \alpha \neq 1, \quad (21)$$

$$u(x, t; 1, \beta) = \frac{m}{2} \left(\log(x + \sqrt{x^2 + \beta e^{-t}}) - \frac{e^{-t}}{\beta} x \left(x - \sqrt{x^2 + \beta e^{-t}} \right) - \frac{t}{2} \right) + n, \quad \alpha = 1,$$

where $\kappa = \sqrt{\alpha}$, and $m > 0, n \in \mathbb{R}$ are integration constants.

As mentioned earlier, in the context of the domain of the local risk tolerance, the function $u(x, t; \alpha, \beta)$ is also well-defined for all $x \in \mathbb{R}$, except in the limit case $\beta \downarrow 0$. This property is particularly useful in indifference valuation, for it eliminates the nonnegativity constraints on the investor's wealth (with and without the claim at hand).

3 American Options under Stochastic Volatility

In this section, we study the forward indifference valuation of an American option in a stochastic volatility model. We work with the exponential forward performance, which, as mentioned in the previous section, corresponds to the parameter choice $\alpha = 0$. A comparative analysis with the classical exponential utility indifference pricing is provided in Section 3.3.

The discounted stock price S is modeled as a diffusion process satisfying

$$dS_t = S_t \sigma(Y_t) (\lambda(Y_t) dt + dW_t). \quad (22)$$

The Sharpe ratio $\lambda(Y_t)$ and volatility coefficient $\sigma(Y_t)$ are driven by a *non-traded* stochastic factor process $(Y_t)_{t \geq 0}$ which evolves according to

$$dY_t = b(Y_t) dt + c(Y_t) (\rho dW_t + \sqrt{1 - \rho^2} d\hat{W}_t). \quad (23)$$

The processes W and \hat{W} are two independent Brownian motions defined on $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t \geq 0}, \mathbb{P})$, where \mathcal{F}_t is taken to be the augmented σ -algebra generated by $((W_u, \hat{W}_u); 0 \leq u \leq t)$. The coefficient $\rho \in (-1, 1)$ accounts for the correlation between S and Y . The volatility function $\sigma(\cdot)$ and the diffusion coefficient $c(\cdot)$ are smooth, positive and bounded. The Sharpe ratio $\lambda(\cdot)$ is bounded continuous, and $b(\cdot)$ is Lipschitz continuous on \mathbb{R} . Similar conditions can be found in Sircar and Zariphopoulou (2005) and, as there, our model excludes the Heston model whose volatility function is not bounded. For indifference pricing under the Heston model, we refer to Grasselli and Hurd (2008).

The American option yields payoff $g(S_\tau, Y_\tau, \tau)$ at any exercise time $\tau \in [0, T]$, where $g(\cdot, \cdot, \cdot)$ is a smooth and bounded function. The holder of the American option dynamically trades in S and the money market, and his discounted trading wealth follows

$$dX_t^\pi = \pi_t \sigma(Y_t) (\lambda(Y_t) dt + dW_t), \quad (24)$$

where $(\pi_t)_{t \geq 0}$ is the discounted cash amount invested in stock (cf. (22)).

3.1 Exponential Forward Indifference Price

We model the American option holder's risk preferences by the exponential forward performance process. This corresponds to the limiting case in (18) where the risk tolerance becomes a constant $\sqrt{\beta}$ (see also Figure 2). As seen in (18), the function $u(x, t)$ is given by

$$u(x, t) = -e^{-\gamma x + \frac{t}{2}}, \quad (25)$$

where $\gamma := 1/\sqrt{\beta}$ can be considered as the investor's *local risk aversion* parameter. In turn, applying Theorem 3, we obtain the exponential forward performance process

$$U_t^e(x) = -e^{-\gamma x + \frac{1}{2} \int_0^t \lambda(Y_s)^2 ds}, \quad t \geq 0. \quad (26)$$

As defined in (7), the option holder's value process based on the exponential forward performance is given by

$$\begin{aligned} V_t^e(X_t) &= \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,sup}_{\pi \in \mathcal{Z}_{t,\tau}} \mathbb{E} \left\{ -e^{-\gamma(X_\tau^\pi + g(S_\tau, Y_\tau, \tau))} e^{\frac{1}{2} \int_0^\tau \lambda(Y_s)^2 ds} \mid \mathcal{F}_t \right\} \\ &= e^{\frac{1}{2} \int_0^t \lambda(Y_s)^2 ds} \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,sup}_{\pi \in \mathcal{Z}_{t,\tau}} \mathbb{E} \left\{ -e^{-\gamma(X_\tau^\pi + g(S_\tau, Y_\tau, \tau))} e^{\frac{1}{2} \int_t^\tau \lambda(Y_s)^2 ds} \mid \mathcal{F}_t \right\}. \end{aligned} \quad (27)$$

We observe that the second term in (27) is the value of a combined stochastic control and optimal stopping problem. Working under the Markovian stochastic volatility market (22)-(23), we look for a candidate optimal \mathcal{F}_t -adapted Markovian strategy by studying the associated HJB variational inequality.

To facilitate notation, we introduce the following differential operators and Hamiltonian:

$$\begin{aligned} \mathcal{L}_{SY} v &= \frac{1}{2} \sigma(y)^2 s^2 v_{ss} + \rho c(y) \sigma(y) s v_{sy} + \frac{1}{2} c(y)^2 v_{yy} + \lambda(y) \sigma(y) s v_s + b(y) v_y, \\ \mathcal{L}_{SY}^0 v &= \frac{1}{2} \sigma(y)^2 s^2 v_{ss} + \rho c(y) \sigma(y) s v_{sy} + \frac{1}{2} c(y)^2 v_{yy} + (b(y) - \rho c(y) \lambda(y)) v_y, \end{aligned} \quad (28)$$

and

$$\mathcal{H}(v_{xx}, v_{xy}, v_{xs}, v_x) = \max_{\pi} \left(\frac{\pi^2 \sigma(y)^2}{2} v_{xx} + \pi (\rho \sigma(y) c(y) v_{xy} + \sigma(y)^2 s v_{xs} + \lambda(y) \sigma(y) v_x) \right).$$

Note that \mathcal{L}_{SY} and \mathcal{L}_{SY}^0 are, respectively, the infinitesimal generators of the Markov process $(S_t, Y_t)_{t \geq 0}$ under the historical measure \mathbb{P} and the minimal martingale measure Q^0 . The latter measure is defined in (35).

Next, we consider the HJB variational inequality:

$$\begin{cases} V_t + \mathcal{L}_{SY}V + \mathcal{H}(V_{xx}, V_{xy}, V_{xs}, V_x) + \frac{\lambda(y)^2}{2}V \leq 0, \\ V(x, s, y, t) \geq -e^{-\gamma(x+g(s,y,t))}, \\ (V_t + \mathcal{L}_{SY}V + \mathcal{H}(V_{xx}, V_{xy}, V_{xs}, V_x) + \frac{\lambda(y)^2}{2}V) \cdot (-e^{-\gamma(x+g(s,y,t))} - V(x, s, y, t)) = 0, \\ V(x, s, y, T) = -e^{-\gamma(x+g(s,y,T))}, \end{cases} \quad (29)$$

for $(x, s, y, t) \in \mathbb{R} \times \mathbb{R}_+ \times \mathbb{R} \times [0, T]$. Given a solution $V(x, s, y, t)$ to (29) that is $\mathcal{C}^{2,2,2,1}$, except across a lower-dimensional optimal exercise boundary, one can show by standard verification arguments (see, for example, Theorem 4.2 of Oksendal and Sulem (2005)) that V is the value function for the combined optimal control/stopping problem in (27). Therefore, we can write

$$V_t^e(X_t) = e^{\frac{1}{2} \int_0^t \lambda(Y_s)^2 ds} V(X_t, S_t, Y_t, t). \quad (30)$$

As it is common in classical indifference pricing problems, the existence of a solution (in an appropriate regularity class) to the HJB equation or variational inequality is a non-trivial and technical issue, and is typically verified in specific cases. For instance, in the classical exponential utility indifference pricing for American options, Oberman and Zariphopoulou (2003) show the existence of a unique viscosity solution of the HJB equation for the value function. In fact, our variational inequality (29) differs from that in Oberman and Zariphopoulou (2003) only by a discounting term $\frac{\lambda(y)^2}{2}V$. For our analysis in this section, we assume the existence of a unique solution $V(x, s, y, t)$ to the variational inequality (29) with the regularity needed for the verification arguments.

Assumption 5 *We assume that there exists a unique solution $V(x, s, y, t)$ to the variational inequality (29) so that (30) holds.*

Applying (26) and (30) to Definition 2, the option holder's exponential forward indifference price function $p(x, s, y, t)$ is given by

$$p(x, s, y, t) = -\frac{1}{\gamma} \log(-V(x, s, y, t)) - x. \quad (31)$$

Then, we substitute (31) into the variational inequality (29) to derive the variational equality for $p(x, s, y, t)$. It turns out that the indifference price is independent of the wealth argument x , and it solves the free boundary problem

$$\begin{cases} p_t + \mathcal{L}_{SY}^0 p - \frac{1}{2} \gamma (1 - \rho^2) c(y)^2 p_y^2 \leq 0, \\ p(s, y, t) \geq g(s, y, t), \\ (p_t + \mathcal{L}_{SY}^0 p - \frac{1}{2} \gamma (1 - \rho^2) c(y)^2 p_y^2) \cdot (g(s, y, t) - p(s, y, t)) = 0, \\ p(s, y, T) = g(s, y, T), \end{cases} \quad (32)$$

for $(s, y, t) \in \mathbb{R}_+ \times \mathbb{R} \times [0, T]$.

By the first-order condition in (29) and the formula (31), the optimal hedging strategy $(\tilde{\pi}_t^*)_{0 \leq t \leq T}$ can be expressed in terms of the partial derivatives of the forward indifference price, namely,

$$\tilde{\pi}_t^* = \frac{\lambda(Y_t)}{\gamma\sigma(Y_t)} + \frac{S_t}{\gamma}p_s(S_t, Y_t, t) + \frac{\rho c(Y_t)}{\gamma\sigma(Y_t)}p_y(S_t, Y_t, t).$$

The first term in this expression is the optimal strategy in (13) when there is no claim. The second and third parts of the strategy $\tilde{\pi}_t^*$ account for the sensitivity of the indifference price with respect to the traded and nontraded assets S and Y respectively.

The optimal exercise time is the first time that the indifference price reaches the option payoff:

$$\tau_t^* = \inf\{t \leq u \leq T : p(S_u, Y_u, u) = g(S_u, Y_u, u)\}. \quad (33)$$

In practice, one can numerically solve the variational inequality (32) to obtain the optimal exercise boundary which represents the critical levels of S and Y at which the option should be exercised. We remark that the indifference price, the optimal hedging and exercising strategies are all wealth independent. The same phenomenon occurs in the classical indifference valuation with exponential utility.

3.2 Dual Representation

The option holder's forward performance maximization in (27) can be considered as the primal optimization problem, and it yields the first expression for the forward indifference price in (31). In this subsection, our objective is to derive a dual representation for the forward indifference price, which turns out to be related to pricing the American option with entropic penalty. This result will allow us to express the price in a way analogous to the classical exponential indifference price. We carry out this comparison in Section 3.3.

First, we denote by $\mathcal{M}(\mathbb{P})$ the set of equivalent local martingale measures with respect to \mathbb{P} on \mathcal{F}_T . As is well-known (see, for example, Frey (1997)), these measures are characterized by their respective density process with respect to \mathbb{P} , which is given by the stochastic exponential

$$Z_t^\phi = \frac{dQ^\phi}{d\mathbb{P}}|_{\mathcal{F}_t} = \exp\left(-\frac{1}{2}\int_0^t \lambda(Y_s)^2 + \phi_s^2 ds - \int_0^t \lambda(Y_s) dW_s - \int_0^t \phi_s d\hat{W}_s\right), \quad (34)$$

where $(\phi_t)_{0 \leq t \leq T}$ is a \mathcal{F}_t -progressively measurable process satisfying $\int_0^T \phi_s^2 ds < \infty$, \mathbb{P} -a.s., and $\mathbb{E}\{Z_T^\phi\} = 1$.

By Girsanov's Theorem, it follows that the two processes $W_t^\phi = W_t + \int_0^t \lambda(Y_s) ds$ and $\hat{W}_t^\phi = \hat{W}_t + \int_0^t \phi_s ds$ are independent Q^ϕ -Brownian motions. The process ϕ is commonly referred to as the *volatility risk premium* for the second Brownian motion \hat{W} . When $\phi = 0$, the resulting measure Q^0 is the well-known *minimal martingale measure* (MMM), whose Radon-Nikodym derivative is

$$\frac{dQ^0}{d\mathbb{P}} = \exp\left(-\frac{1}{2}\int_0^T \lambda(Y_s)^2 ds - \int_0^T \lambda(Y_s) dW_s\right). \quad (35)$$

See Föllmer and Schweizer (1990).

Next, we define the conditional relative entropy of Q^ϕ with respect to \mathbb{P} over the interval $[t, \tau]$, with $\tau \in \mathcal{T}_{t,T}$, as

$$H_t^\tau(Q^\phi|\mathbb{P}) := \mathbb{E}^{Q^\phi}\left\{\log \frac{Z_\tau^\phi}{Z_t^\phi} | \mathcal{F}_t\right\}. \quad (36)$$

Direct computation from (34) shows that this relative entropy is, in fact, a quadratic penalization on the risk premia λ and ϕ . In other words,

$$H_t^\tau(Q^\phi|\mathbb{P}) = \frac{1}{2}\mathbb{E}^{Q^\phi} \left\{ \int_t^\tau \lambda(Y_s)^2 + \phi_s^2 ds | \mathcal{F}_t \right\}. \quad (37)$$

We denote the set of equivalent local martingale measures with finite relative entropy (with respect to \mathbb{P}) as

$$\mathcal{M}_f := \left\{ Q^\phi \in \mathcal{M}(\mathbb{P}) : H_0^T(Q^\phi|\mathbb{P}) < \infty \right\}.$$

The probability measure that yields the minimum relative entropy with respect to \mathbb{P} is called the *minimal entropy martingale measure* (MEMM), and it is defined by

$$Q^E := \arg \min_{Q^\phi \in \mathcal{M}(\mathbb{P})} H_t^T(Q^\phi|\mathbb{P}). \quad (38)$$

Key results on the MEMM in a general semimartingale market framework can be found in Frittelli (2000) and Grandits and Rheinländer (2002). This measure also arises in hedging or indifference valuation under exponential utility, see Delbaen et al. (2002) and Rouge and El Karoui (2000), among others.

Remark 6 *If the Sharpe ratio is constant, i.e. $\lambda(y) = \lambda$, then the conditional relative entropy simplifies to*

$$H_t^T(Q^\phi|\mathbb{P}) = \frac{\lambda^2}{2}(T-t) + \mathbb{E}^{Q^\phi} \left\{ \int_t^T \phi_s^2 ds | \mathcal{F}_t \right\} \geq \frac{\lambda^2}{2}(T-t).$$

As a result, setting $\phi = 0$ minimizes $H_t^T(Q^\phi|\mathbb{P})$. This is a well-known example where the MEMM Q^E coincides with the MMM Q^0 .

We can also express any measure Q^ϕ in terms of Q^0 via the Radon-Nikodym derivative, namely,

$$\frac{dQ^\phi}{dQ^0} = \frac{dQ^\phi}{d\mathbb{P}} \bigg/ \frac{dQ^0}{d\mathbb{P}} = \exp \left(-\frac{1}{2} \int_0^T \phi_s^2 ds - \int_0^T \phi_s d\hat{W}_s^0 \right). \quad (39)$$

We denote the density process of Q^ϕ with respect to Q^0 by $Z_t^{\phi,0} = \mathbb{E}^{Q^0} \left\{ \frac{dQ^\phi}{dQ^0} | \mathcal{F}_t \right\}$.

Treating Q^0 as the prior risk-neutral measure, we can define the conditional relative entropy $H_t^\tau(Q^\phi|Q^0)$ of Q^ϕ with respect to Q^0 over the interval $[t, \tau]$ as

$$H_t^\tau(Q^\phi|Q^0) = \mathbb{E}^{Q^\phi} \left\{ \log \frac{Z_\tau^{\phi,0}}{Z_t^{\phi,0}} | \mathcal{F}_t \right\} = \frac{1}{2} \mathbb{E}^{Q^\phi} \left\{ \int_t^\tau \phi_s^2 ds | \mathcal{F}_t \right\}. \quad (40)$$

With these notations, we are now ready to state the duality formula for the exponential forward indifference price.

Proposition 7 *The American option holder's exponential forward indifference price $p(s, y, t)$ is the solution of the combined stochastic control and optimal stopping problem:*

$$p(S_t, Y_t, t) = \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,inf}_{Q^\phi \in \mathcal{M}_f} \left(\mathbb{E}^{Q^\phi} \{ g(S_\tau, Y_\tau, \tau) | \mathcal{F}_t \} + \frac{1}{\gamma} H_t^\tau(Q^\phi|Q^0) \right). \quad (41)$$

We can view this dual representation (41) as an alternative interpretation of the forward indifference price. In essence, the holder tries to value the American option over a set of equivalent local martingale measures, and his selection criterion for the optimal pricing measure is based on relative entropic penalization (scaled by risk aversion γ). Indeed, the second term in (41) is the relative entropy of a candidate measure Q^ϕ with respect to the MMM Q^0 up to the exercise time. This leads the holder to assign the corresponding optimal risk premium ϕ^* according to (42). Due to the entropic penalty, we observe from (41) that the exponential forward indifference pricing rule is nonlinear in terms of the number of options held.

There are two ways to establish Proposition 7. The first approach is to apply the variational inequalities in Section 3.1. Given enough regularity of the solution to the HJB VI (32), then one can apply the transformation (31) and check that the resulting HJB variational inequality (32) is identical to that for the stochastic control/stopping problem in (41). Using this approach, the associated optimal control ϕ^* must satisfy

$$\phi_t^* = -\gamma c(Y_t) \sqrt{1 - \rho^2} p_y(S_t, Y_t, t), \quad 0 \leq t \leq T, \quad (42)$$

subject to integrability condition so that $Q^{\phi^*} \in \mathcal{M}_f$.

In the next subsection, we will provide the other alternative approach which does not involve the variational inequalities. The key of the proof therein is to use an analogous duality formula from the classical exponential indifference pricing (see Theorem 8 below). Before we present the proof, we first need to recall and discuss the classical exponential utility indifference price.

3.3 Comparison with the Classical Exponential Utility Indifference Price

In this section, we first summarize the duality results from the classical exponential utility indifference pricing, and then apply them to derive the forward indifference formula (41). Moreover, we also provide a comparative analysis between the classical and forward indifference valuation.

We start with a brief review of the classical indifference pricing with exponential utility under stochastic volatility models. We refer the reader to, for example, Sircar and Zariphopoulou (2005), Benth and Karlsen (2005), and Grasselli and Hurd (2008) for European-style derivatives, as well as Oberman and Zariphopoulou (2003) and Leung and Sircar (2009b) for American options.

In the classical setting, the investor's risk preferences at time T are modeled by the exponential utility function $-e^{-\gamma x}$, with risk aversion parameter $\gamma > 0$. In the stochastic volatility model described in (22)-(23), the value function of the Merton problem (cf. (4)) is

$$M(X_t, Y_t, t) = \sup_{\pi \in \mathcal{Z}_{t,T}} \mathbb{E} \{ -e^{-\gamma X_T^\pi} | \mathcal{F}_t \}, \quad (43)$$

with $(X_t^\pi)_{t \geq 0}$ given by (24).

As is well known, see for example, Delbaen et al. (2002) and Rouge and El Karoui (2000), the Merton value function admits a dual representation in terms of relative entropy minimization, namely,

$$M(X_t, Y_t, t) = -\exp \left(-\gamma X_t - H_t^T(Q^E | \mathbb{P}) \right), \quad (44)$$

where $H_t^T(Q^E | \mathbb{P})$ is the conditional relative entropy of Q^E with respect to \mathbb{P} over $[t, T]$.

If the American option g is held, then the investor seeks the optimal trading strategy and exercise time to maximize the expected utility of wealth from both his dynamic portfolio and the option's payoff at exercise. Upon exercise of the option, the investor will reinvest the

contract proceeds, if any, to his trading portfolio, and continue to trade up to time T . As a consequence, the holder faces the optimization problem

$$\hat{V}(X_t, S_t, Y_t, t) = \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,sup}_{\pi \in \mathcal{Z}_{t,\tau}} \mathbb{E} \left\{ M(X_\tau^\pi + g(S_\tau, Y_\tau, \tau), Y_\tau, \tau) \mid \mathcal{F}_t \right\} \quad (45)$$

$$= \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,sup}_{\pi \in \mathcal{Z}_{t,\tau}} \mathbb{E} \left\{ -e^{-\gamma(X_\tau^\pi + g(S_\tau, Y_\tau, \tau))} e^{-H_\tau^T(Q^E|\mathbb{P})} \mid \mathcal{F}_t \right\}, \quad (46)$$

where M is defined in (43). The classical indifference price \hat{p} of the American option is then found from the equation

$$M(x, y, t) = \hat{V}(x - \hat{p}(x, s, y, t), s, y, t). \quad (47)$$

Under a general semimartingale framework, Leung and Sircar (2009b) have derived a duality formula for the optimization problem (45) and the exponential indifference price \hat{p} . We summarize the result here written for our stochastic volatility market setting. We use the shorthand notation $\mathbb{E}_t^{Q^\phi} \{\cdot\} \equiv \mathbb{E}^{Q^\phi} \{\cdot \mid \mathcal{F}_t\}$.

Theorem 8 (*Propositions 2.4 and 2.8 of Leung and Sircar (2009b)*) *The classical value function for holding an American option g is given by*

$$\begin{aligned} \hat{V}(X_t, S_t, Y_t, t) \\ = -e^{-\gamma X_t} \exp \left(- \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,inf}_{Q^\phi \in \mathcal{M}_f} \left(\mathbb{E}_t^{Q^\phi} \{ \gamma g(S_\tau, Y_\tau, \tau) \} + H_t^T(Q^\phi|\mathbb{P}) + \mathbb{E}_t^{Q^\phi} \{ H_\tau^T(Q^E|\mathbb{P}) \} \right) \right). \end{aligned} \quad (48)$$

The classical exponential indifference price is given by

$$\hat{p}(S_t, Y_t, t) = \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,inf}_{Q^\phi \in \mathcal{M}_f} \left(\mathbb{E}_t^{Q^\phi} \{ g(S_\tau, Y_\tau, \tau) \} + \frac{1}{\gamma} H_t^T(Q^\phi|Q^E) \right). \quad (49)$$

Now, we apply Theorem 8 to establish Proposition 7.

Proof of Proposition 7. We begin by writing the function $V(X_t, S_t, Y_t, t)$ in (30) as

$$\begin{aligned} V(X_t, S_t, Y_t, t) &= \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,sup}_{\pi \in \mathcal{Z}_{t,\tau}} \mathbb{E} \left\{ -e^{-\gamma(X_\tau^\pi + g(S_\tau, Y_\tau, \tau) - \frac{1}{2\gamma} \int_t^\tau \lambda(Y_s)^2 ds)} \mid \mathcal{F}_t \right\} \\ &= \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,sup}_{\pi \in \mathcal{Z}_{t,\tau}} \mathbb{E} \left\{ -e^{-\gamma(X_\tau^\pi + \tilde{g}(S_\tau, Y_\tau, \tau))} e^{-H_\tau^T(Q^E|\mathbb{P})} \mid \mathcal{F}_t \right\}, \end{aligned}$$

where

$$\tilde{g}(S_\tau, Y_\tau, \tau) = g(S_\tau, Y_\tau, \tau) - \frac{1}{2\gamma} \int_t^\tau \lambda(Y_s)^2 ds - \frac{1}{\gamma} H_\tau^T(Q^E|\mathbb{P}).$$

In other words, the optimization problem $V(X_t, S_t, Y_t, t)$ has the same form as $\hat{V}(X_t, S_t, Y_t, t)$ in (48), but with a new option payoff $\tilde{g}(S_\tau, Y_\tau, \tau)$, instead of $g(S_\tau, Y_\tau, \tau)$, at any exercise time $\tau \in \mathcal{T}_{t,T}$.

Therefore, substituting the payoff \tilde{g} for g in Theorem 8 yields that

$$\begin{aligned}
V(X_t, S_t, Y_t, t) &= -e^{-\gamma X_t} \exp \left(- \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,inf}_{Q^\phi \in \mathcal{M}_f} \left(\mathbb{E}_t^{Q^\phi} \{ \gamma \tilde{g}(S_\tau, Y_\tau, \tau) \} + H_t^\tau(Q^\phi | \mathbb{P}) + \mathbb{E}_t^{Q^\phi} \{ H_\tau^T(Q^E | \mathbb{P}) \} \right) \right) \\
&= -e^{-\gamma X_t} \exp \left(- \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,inf}_{Q^\phi \in \mathcal{M}_f} \left(\mathbb{E}_t^{Q^\phi} \left\{ \gamma g(S_\tau, Y_\tau, \tau) - \frac{1}{2} \int_t^\tau \lambda(Y_s)^2 ds \right\} + H_t^\tau(Q^\phi | \mathbb{P}) \right) \right) \\
&= -e^{-\gamma X_t} \exp \left(- \operatorname{ess\,sup}_{\tau \in \mathcal{T}_{t,T}} \operatorname{ess\,inf}_{Q^\phi \in \mathcal{M}_f} \left(\mathbb{E}_t^{Q^\phi} \{ \gamma g(S_\tau, Y_\tau, \tau) \} + H_t^\tau(Q^\phi | Q^0) \right) \right), \tag{50}
\end{aligned}$$

where the last equality follows from (36) and (40). This is an alternative representation for V in (30). Finally, applying the duality formula (50) to (31) yields the indifference price formula (41). ■

The classical and forward indifference prices in Theorem 8 and Proposition 7 bear a striking similarity, except the relative entropy term in (49) is computed with respect to Q^E , but in (41) it is computed with respect to Q^0 . To highlight this, we shall compare the variational inequality of the forward indifference price in (32) with its classical analogue.

As is well known, the classical Merton function M admits a separation of variables due to the exponential utility.

Proposition 9 *The value function $M(x, y, t)$ is given by*

$$M(x, y, t) = -e^{-\gamma x} f(y, t)^{\frac{1}{1-\rho^2}}, \tag{51}$$

where ρ is the correlation coefficient in (23), and f solves

$$f_t + \mathcal{L}_Y^0 f = \frac{1}{2}(1 - \rho^2)\lambda(y)^2 f, \tag{52}$$

for $(x, t) \in \mathbb{R} \times [0, T)$, with $f(y, T) = 1$, for $y \in \mathbb{R}$. The operator \mathcal{L}_Y^0 is the infinitesimal generator of Y under the MMM Q^0 , and is given by

$$\mathcal{L}_Y^0 f = \frac{1}{2}c(y)^2 f_{yy} + (b(y) - \rho c(y)\lambda(y)) f_y.$$

Details can be found, for example, in Theorem 2.2 of Sircar and Zariphopoulou (2005).

Using (51) and (47), we obtain the formula

$$\hat{V}(x, s, y, t) = -e^{-\gamma(x + \hat{p}(x, s, y, t))} f(y, t)^{\frac{1}{1-\rho^2}}. \tag{53}$$

To derive the variational inequality for the indifference price, one can use the variational inequality for V and then apply the transformation (53). Again, the choice of exponential utility yields wealth-independent indifference prices, i.e. $\hat{p}(x, s, y, t) = \hat{p}(s, y, t)$. We obtain

$$\begin{cases} \hat{p}_t + \mathcal{L}_{SY}^E \hat{p} - \frac{1}{2}\gamma(1 - \rho^2)c(y)^2 \hat{p}_y^2 \leq 0, \\ \hat{p}(s, y, t) \geq g(s, y, t), \\ \left(\hat{p}_t + \mathcal{L}_{SY}^E \hat{p} - \frac{1}{2}\gamma(1 - \rho^2)c(y)^2 \hat{p}_y^2 \right) \cdot (g(s, y, t) - \hat{p}(s, y, t)) = 0, \\ \hat{p}(s, y, T) = g(s, y, T), \end{cases} \tag{54}$$

for $(s, y, t) \in \mathbb{R}_+ \times \mathbb{R}_+ \times [0, T]$. Here, \mathcal{L}_{SY}^E is the infinitesimal generator of (S, Y) under the MEMM Q^E defined by

$$\mathcal{L}_{SY}^E w = \mathcal{L}_{SY}^0 w + l(y, t) c(y) \sqrt{1 - \rho^2} w_y, \quad (55)$$

where \mathcal{L}_{SY}^0 is given in (28) and

$$l(y, t) = \frac{1}{\sqrt{1 - \rho^2}} c(y) \frac{f_y(y, t)}{f(y, t)}. \quad (56)$$

As shown in Section 2 of Sircar and Zariphopoulou (2005), the function $l(y, t)$ is smooth and bounded, and is the risk premium corresponding to the minimal entropy martingale measure (MEMM) Q^E , namely,

$$\frac{dQ^E}{d\mathbb{P}} = \exp \left(-\frac{1}{2} \int_0^T (\lambda(Y_s)^2 + l(Y_s, s)^2) ds - \int_0^T \lambda(Y_s) dW_s + \int_0^T l(Y_s, s) d\hat{W}_s \right). \quad (57)$$

Therefore, the operator \mathcal{L}_{SY}^E is the infinitesimal generator of (S, Y) under Q^E .

It is important to notice that the fundamental difference between variational inequalities (32) and (54) lies in the operators \mathcal{L}_{SY}^0 in (28) and \mathcal{L}_{SY}^E in (55). Indeed, these two variational inequalities, respectively, reflect the special roles of the MMM in the forward indifference setting and the MEMM in the classical model.

Note that the classical indifference price \hat{p} in (54) involves the MEMM operator \mathcal{L}_{SY}^E , which in turn depends on $f(t, y)$. Therefore, the computation of \hat{p} requires first solving PDE (52) followed by variational inequality (54). However, in the forward indifference valuation, the indifference price can be obtained by solving only one variational inequality (32). Hence, with exponential performance, the forward indifference formulation allows for more efficient computation than in the classical framework.

Remark 10 *If the claim is written on Y only, say with payoff function $g(y, t)$, then the indifference price does not depend on S . Applying a logarithmic transformation to the variational inequality (32), the nonlinear variational inequality can be linearized. As a result, in addition to (41), the forward indifference price admits the representation:*

$$p(y, t) = -\frac{1}{\gamma(1 - \rho^2)} \log \inf_{\tau \in \mathcal{T}_{t, T}} \mathbb{E}^{Q^0} \left\{ e^{-\gamma(1 - \rho^2)g(Y_\tau, \tau)} | Y_t = y \right\}. \quad (58)$$

In contrast, the classical exponential utility indifference price of an American option with the same payoff function $g(y, t)$ can be found in Oberman and Zariphopoulou (2003), and it is given by

$$\hat{p}(y, t) = -\frac{1}{\gamma(1 - \rho^2)} \log \inf_{\tau \in \mathcal{T}_{t, T}} \mathbb{E}^{Q^E} \left\{ e^{-\gamma(1 - \rho^2)g(Y_\tau, \tau)} | Y_t = y \right\}, \quad (59)$$

with Q^E given in (57). Again, we see that the measure Q^0 in the forward performance framework plays a similar role as Q^E in the classical setting.

Remark 11 *If the Sharpe ratio λ is constant, then the measures Q^0 and Q^E coincide by Remark 6. In fact, direct substitution shows that the function $f(t) := e^{-(1 - \rho^2)\frac{\lambda^2}{2}(T - t)}$ solves the PDE (52). This implies that $l(y, t) = 0$ and $Q^E = Q^0$. As a result, the classical and forward indifference prices in (58) and (59) above, where the claim is written on Y only, are in fact identical.*

3.4 Risk Aversion and Volume Asymptotics

Proposition 7 provides a convenient representation for analyzing the exponential forward indifference price's sensitivity with respect to risk aversion and the number of options held. Next, we further elaborate on these dependencies.

First, let us consider a risk-averse investor with local risk aversion γ who holds $a > 0$ units of American options, and suppose that all a units are constrained to be exercised simultaneously. In this case, the holder's indifference price $p(s, y, t; \gamma, a)$ is again given by (41) but with the payoff $g(S_\tau, Y_\tau, \tau)$ replaced by $ag(S_\tau, Y_\tau, \tau)$. The optimal exercise time $\tau^*(a, \gamma)$ is the first time that the forward indifference price reaches the payoff from exercising all a units:

$$\tau^*(a, \gamma) = \inf\{t \leq u \leq T : p(S_u, Y_u, u; \gamma, a) = ag(S_u, Y_u, u)\}. \quad (60)$$

Proposition 12 Fix $a > 0$ and $t \in [0, T]$. If $\gamma_2 \geq \gamma_1 > 0$, then

$$p(s, y, t; \gamma_2, a) \leq p(s, y, t; \gamma_1, a)$$

and

$$\tau^*(a, \gamma_2) \leq \tau^*(a, \gamma_1), \quad \text{almost surely.}$$

Proof. For $\gamma_2 \geq \gamma_1 > 0$, it follows from (41) that $p(s, y, t; \gamma_2, a) \leq p(s, y, t; \gamma_1, a)$. Therefore, as γ increases, $p(s, y, t; \gamma, a)$ decreases, while the payoff $ag(s, y, t)$ does not depend on γ . By (60), this leads to a shorter exercise time (almost surely). ■

Furthermore, we deduce formally the risk-aversion limits of the indifference price. For the technical details, we refer the reader to Leung and Sircar (2009b) who have shown these asymptotic results for the traditional exponential indifference price of American options in a general semimartingale framework, and their proofs can be easily adapted here.

First, as γ increases to infinity, the penalty term in the indifference price representation (41) vanishes. Consequently, we deduce the following limit:

$$\lim_{\gamma \rightarrow \infty} p(s, y, t; \gamma, a) = a \cdot \sup_{\tau \in \mathcal{T}_{t,T}} \inf_{Q^\phi \in \mathcal{M}_f} \mathbb{E}^{Q^\phi} \{g(S_\tau, Y_\tau, \tau) | S_t = s, Y_t = y\} =: a \cdot \underline{c}(s, y, t). \quad (61)$$

This limiting price is $\underline{c}(s, y, t)$ commonly referred to as the sub-hedging price of the American options (see, for example, Karatzas and Kou (1998)). Interestingly, the classical indifference price also converges to the same limit as $\gamma \rightarrow \infty$ (see Proposition 2.17 of Leung and Sircar (2009b)).

On the other hand, as the holder's risk aversion γ decreases to zero, one can deduce from (41) that it is optimal not to deviate from the prior measure Q^0 (i.e. $\phi = 0$), yielding zero entropic penalty. This leads to valuing the American options under the MMM Q^0 , namely,

$$\lim_{\gamma \rightarrow 0} p(s, y, t; \gamma, a) = a \cdot \sup_{\tau \in \mathcal{T}_{t,T}} \mathbb{E}^{Q^0} \{g(S_\tau, Y_\tau, \tau) | S_t = s, Y_t = y\}. \quad (62)$$

In contrast, the classical indifference price converges to the risk-neutral price of the American options under the MEMM Q^E instead of Q^0 .

Finally, the forward indifference prices satisfy the volume-scaling property:

$$p(s, y, t; \gamma, a)/a = p(s, y, t; a\gamma, 1).$$

As the number of options held increases, the average indifference prices, $p(s, y, t; \gamma, a)/a$ will decrease, and by (60) the options will be exercised earlier. The classical indifference price for American options also possesses the same volume-scaling property and exercise phenomenon.

Moreover, the indifference price limits in (61)-(62) lead to the large risk-aversion limit:

$$\lim_{a \rightarrow \infty} \frac{p(s, y, t; \gamma, a)}{a} = \underline{c}(s, y, t),$$

which is the sub-hedging price, and the zero risk-aversion limit:

$$\lim_{a \rightarrow 0} \frac{p(s, y, t; \gamma, a)}{a} = \sup_{\tau \in \mathcal{T}_{t,T}} \mathbb{E}^{Q^0} \{g(S_\tau, Y_\tau, \tau) | S_t = s, Y_t = y\}.$$

To summarize, in all these limiting cases, both the classical and forward indifference pricing rules become *linear* with respect to quantity. In the large risk-aversion and large volume limits, the classical and forward indifference price will both converge to the sub-hedging price. However, in the zero risk-aversion and zero volume limits, the classical and forward indifference prices, respectively, converge to the risk-neutral prices under the MEMM Q^E and the MMM Q^0 . As pointed out in Remark 6, when the Sharpe ratio λ is constant, the MEMM and MMM coincide, so the corresponding zero risk-aversion and zero volume limits of the classical and forward indifference prices will be the same.

4 Modeling Early Exercises of Employee Stock Options

Now, we consider the problem of exercising employee stock options (ESOs) under a time-monotone forward performance criterion with the risk tolerance function $R(x, t; \alpha, \beta)$ in (17). These options are American calls granted by a company to its employees as a form of compensation. A typical ESO contract prohibits the employee from selling the option and from hedging by short selling the firm's stock. The sale and hedging restrictions may induce the employee to exercise the ESO early and invest the option proceeds elsewhere. Modeling the employee's exercise timing is crucial to the accurate valuation of ESOs.

Empirical studies (for example, Bettis et al. (2005)) show that employees tend to exercise their ESOs very early. Recent studies, for example, Henderson (2005) and Leung and Sircar (2009a), apply classical indifference pricing to ESO valuation. In those papers, the employee was assumed to have a classical exponential utility specified at the expiration date T of the options. Here, we assume a forward performance criterion for the employee, which is not anchored to a specific future time, and then numerically solve for the optimal exercise strategies under different scenarios.

We assume that the employee trades dynamically in a liquid correlated market index and a riskless money market account in order to partially hedge against his ESO position. Alternative hedging strategies for ESOs have also been proposed. For instance, Leung and Sircar (2009b) considered combining static hedges with market-traded European or American puts with the dynamic investment in the market index.

We focus our study on the case of a single ESO. Typically, ESOs have a vesting period during which they cannot be exercised early. The incorporation of a vesting period amounts to lifting the employee's pre-vesting exercise boundary to infinity to prevent exercise, but leaving the post-vesting policy unchanged. The case with multiple ESOs can be studied as a straightforward extension to our model though the numerical computations will be more complex and time-consuming; see Grasselli and Henderson (2009) for the case of multiple perpetual ESOs with exponential utility. Our main objective is to examine the non-trivial effects of forward investment performance criterion on the employee's optimal exercise timing.

4.1 The Employee's Optimal Forward Performance with an ESO

We assume that the money market account yields a constant interest rate $r \geq 0$. The *discounted* prices of the market index and the firm's stock are modeled as correlated lognormal processes, namely,

$$dS_t = S_t \sigma (\lambda dt + dW_t), \quad (\text{traded}) \quad (63)$$

$$dY_t = bY_t dt + cY_t (\rho dW_t + \sqrt{1 - \rho^2} d\hat{W}_t), \quad (\text{non-traded}) \quad (64)$$

where λ, σ, b, c are constant parameters. The discounted ESO payoff, with expiration date T , is given by

$$g(Y_\tau, \tau) = (Y_\tau - Ke^{-r\tau})^+, \quad \text{for } \tau \in \mathcal{T}_{0,T}.$$

Note that this market setup is nested in the Itô diffusion market described in Section 2. Here, the Sharpe ratio λ of S is now a constant, and the option payoff is independent of S . The employee trades dynamically in the index Y and the money market account, so his discounted wealth process satisfies

$$dX_t^\pi = \pi_t \sigma (\lambda dt + dW_t). \quad (65)$$

We proceed with the employee's forward performance criterion $U_t(x)$. First, we adopt the risk tolerance function in (17), namely, $R(x, t) = \sqrt{\alpha x^2 + \beta e^{-\alpha t}}$, and the corresponding dynamic risk preference function $u(x, t)$ given in Proposition 4. Then, we apply Theorem 3 to obtain the employee's forward performance $U_t(x) = u(x, \lambda^2 t)$. In turn, the employee's maximal forward performance in the presence of the ESO is given by

$$V(x, y, t) = \sup_{\tau \in \mathcal{T}_{t,T}} \sup_{\pi \in \mathcal{Z}_{t,\tau}} \mathbb{E} \{ u(X_\tau^\pi + g(Y_\tau, \tau), \lambda^2 \tau) \mid X_t = x, Y_t = y \}. \quad (66)$$

In contrast to the stochastic volatility problem in Section 3, the option payoff depends on Y only, and the state variable S disappears from the value function V .

To solve for the employee's value function, we look for a solution to the following HJB variational inequality:

$$\begin{cases} V_t + \mathcal{L}_Y V - \frac{(\rho c y V_{xy} + \lambda V_x)^2}{2V_{xx}} \leq 0, \\ V(x, y, t) \geq u(x + g(y, t), \lambda^2 t), \\ (V_t + \mathcal{L}_Y V - \frac{(\rho c y V_{xy} + \lambda V_x)^2}{2V_{xx}}) \cdot (u(x + g(y, t), \lambda^2 t) - V(x, y, t)) = 0, \\ V(x, y, T) = u(x + g(y, T), \lambda^2 T), \end{cases} \quad (67)$$

for $(x, y, t) \in \mathbb{R} \times \mathbb{R}_+ \times [0, T]$, with $\mathcal{L}_Y V = \frac{1}{2}c(y)^2 V_{yy} + b(y)V_y$.

We remark that the variational inequality (67) is highly nonlinear, and it can be simplified only for very special local utility functions. In the exponential forward performance case, this can be viewed as a special case under the stochastic volatility model discussed in Section 3. In the perpetual case with exponential utility and $r = 0$, Henderson (2007) derives an explicit solution for the value function. Recent ESO valuation models, such as Henderson (2005), Grasselli and Henderson (2009), and Leung and Sircar (2009a), are also designed with the classical exponential utility. As for the general case, we do not attempt to address the related existence, uniqueness, and regularity questions.

4.2 Numerical Solutions

We apply a *fully explicit* finite-difference scheme to numerically solve (67) for the employee's optimal exercising strategy. First, we restrict the domain $\mathbb{R} \times \mathbb{R}_+ \times [0, T]$ to a finite domain $\mathcal{D} = \{(x, y, t) : -L_1 \leq x \leq L_2, 0 \leq y \leq L_3, 0 \leq t \leq T\}$, where L_k , $k = 1, 2, 3$, are chosen to be sufficiently large to preserve the accuracy of the numerical solutions.

Next, a number of boundary conditions are imposed. Along $y = 0$, the firm's stock price, and thus the ESO, become worthless. Therefore, we set $V(x, 0, t) = u(x, \lambda^2 t)$. When Y hits the high level L_3 , we assume that the ESO will be exercised there, implying the condition

$$V(x, L_3, t) = u(x + g(L_3, t), \lambda^2 t).$$

Along $x = -L_1$ and $x = L_2$, we adopt the Dirichlet boundary conditions

$$V(-L_1, y, t) = u(-L_1 + g(y, t), \lambda^2 t) \quad \text{and} \quad V(L_2, y, t) = u(L_2 + g(y, t), \lambda^2 t),$$

which imply that the employee will exercise the ESO at these boundaries. Over a uniform grid, we apply an explicit finite-difference approximations and solve for V iteratively backward in time starting at T .

At each time step, the inequality constraint $V(x, y, t) \geq u(x + g(y, t), \lambda^2 t)$ is enforced. By comparing the value function and the obstacle term, we identify the *continuation region* \mathcal{C} where the ESO is not exercised, and the *exercise region* \mathcal{E} where it is exercised, namely

$$\mathcal{C} = \{(x, y, t) \in \mathbb{R} \times \mathbb{R}_+ \times [0, T] : V(x, y, t) > u(x + g(y, t), \lambda^2 t)\}, \quad (68)$$

$$\mathcal{E} = \{(x, y, t) \in \mathbb{R} \times \mathbb{R}_+ \times [0, T] : V(x, y, t) = u(x + g(y, t), \lambda^2 t)\}. \quad (69)$$

From the numerical example in Figure 3, we observe that the value function dominates the obstacle term. At any time t and wealth x , we locate the optimal stock price level $y^*(x, t)$ that separates the two regions \mathcal{C} and \mathcal{E} . As a result, the employee will exercise the ESO as soon as Y_t hits the threshold $y^*(X_t, t)$:

$$\tau^* = \inf\{0 \leq t \leq T : Y_t = y^*(X_t, t)\}. \quad (70)$$

In the case of call options, the boundary lies above the strike K . Figure 4 shows an example of the optimal exercise boundary for the ESO.

4.3 Behavior of the Optimal Exercise Policy

We illustrate the employee's optimal exercise boundary in Figure 4. Not surprisingly, the exercise boundary $y^*(x, t)$ decreases with respect to time, which implies that the employee is willing to exercise the ESO at a lower stock price as it gets closer to expiry.

From Figure 5, we observe that the exercise boundary is wealth dependent. The employee tends to delay exercising the ESO when his wealth deviates away from zero. We can gain some intuition from our choice of risk tolerance function $R(x, t; \alpha, \beta)$. As wealth approaches zero, the employee's risk tolerance decreases (recall Figure 1), or equivalently, risk aversion increases. Higher risk aversion influences the employee to exercise earlier to secure small gains rather than waiting for future uncertain payoffs.

Finally, we show in Figure 6 that the exercise boundary tends to shift upward for higher values of α and β , given the initial wealth $x = 0$. The effect of β is intuitive because the risk tolerance function is increasing with respect to β . Therefore, the option holder with a higher β is effectively less risk averse and may be willing to hold on to the ESO longer.

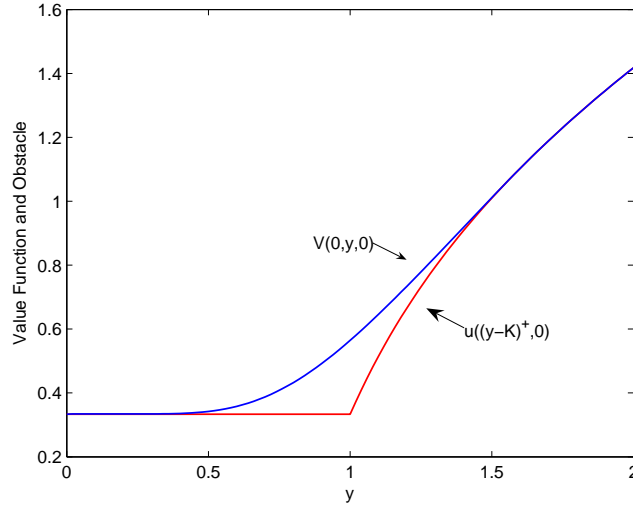


Figure 3: The value function $V(x, y, t)$ dominates the obstacle term $u(x + g(y, t), \lambda^2 t)$. The parameters are $\lambda = 33\%$, $\sigma = 35\%$, $b = 6\%$, $c = 40\%$, $\rho = 50\%$, $r = 1\%$, $K = 1$, $T = 1$, $\alpha = 4$, $\beta = 0.25$. At $t = 0$ and $x = 0$, the critical stock price $y^*(0, 0) = 1.58$ is the point at which the value function touches the obstacle term (above the strike).

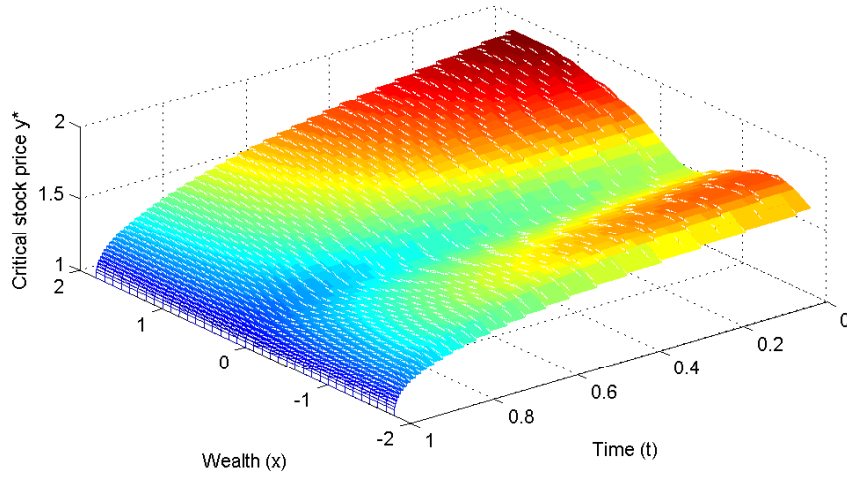


Figure 4: The optimal exercise policy is characterized by the critical stock price $y^*(x, t)$ as a function of wealth x and time t . It decreases as time approaches maturity. In addition, it tends to shift lower as wealth is near zero.

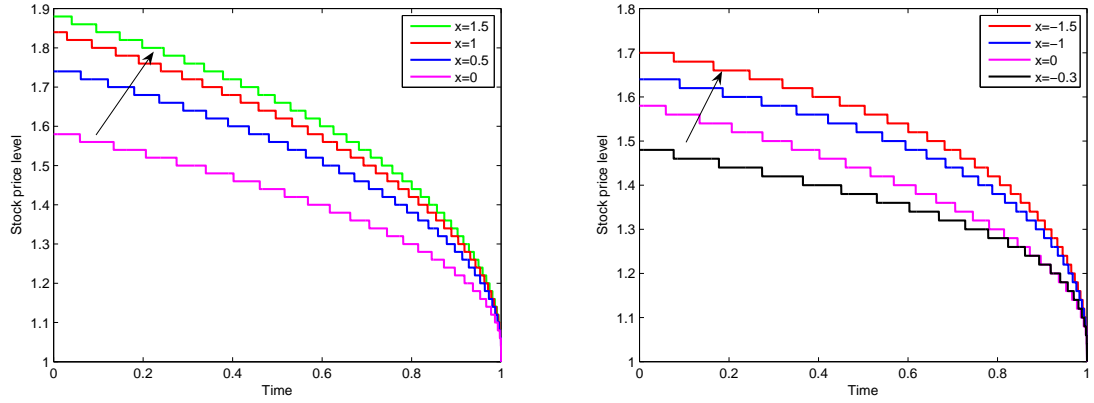


Figure 5: (Left): The exercise boundary shifts upward as wealth increases from zero. (Right): The exercise boundary is the lowest when wealth $x = -0.3$. As wealth further decreases from -0.3 to -1.5 , the exercise boundary rises again. The parameters here are the same as in Figure 3.

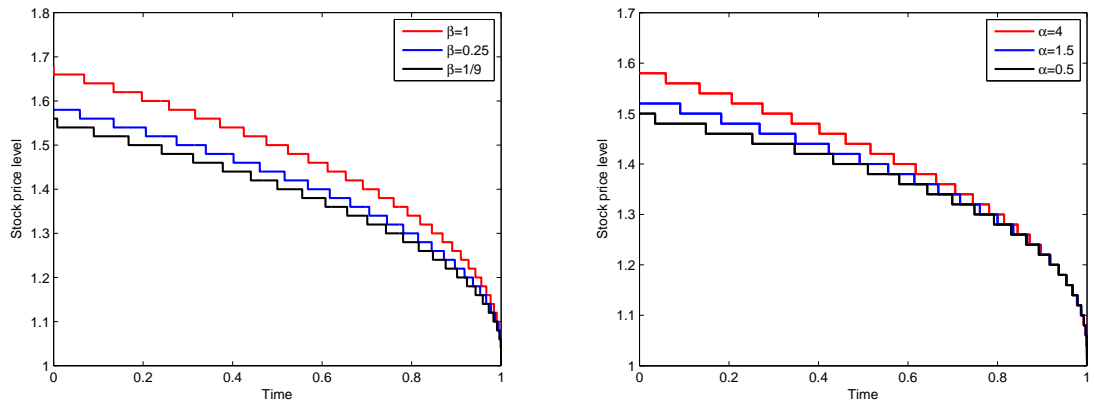


Figure 6: (Left): A higher value of β leads to a higher exercise boundary (at initial wealth $x = 0$). (Right): A higher value of α shifts the exercise boundary upward (initial wealth $x = 0$). The parameters here are taken to be same as those in Figure 3, except for α and β specified in the figures above.

5 Marginal Forward Indifference Price of American Options

In this section, we introduce the marginal forward indifference price of American options. A related concept in the classical utility framework is the *marginal utility price* introduced by Davis (1997), which is useful as an approximation for pricing a small number of claims. For completeness and the upcoming comparison with the forward analogue, we provide a brief review of the marginal utility price in the diffusion market.

5.1 The Classical Marginal Utility Price

In traditional utility maximization, the investor's risk aversion is modeled by a deterministic utility function, say $\hat{U}(x)$, defined at time T . In the Itô diffusion market introduced in Section 2, the investor trades dynamically between the money market and stock S , and solves the Merton portfolio optimization problem in (4).

Next, suppose that the investor decides to buy δ units of a European claim, each offering payoff $C_T \in \mathcal{F}_T$. The marginal utility price is defined as the per-unit price that the investor is willing to pay for an infinitesimal position ($\delta \approx 0$) in the claim. This concept is introduced by Davis (1997). He shows by a formal small δ expansion that the investor's marginal utility price at time t is given by

$$\hat{h}_t = \frac{\mathbb{E} \left\{ \hat{U}'(\hat{X}_T^*) C_T \mid \mathcal{F}_t \right\}}{M'_t(X_t)}, \quad t \in [0, T], \quad (71)$$

where \hat{X}_T^* is the optimal terminal wealth for the Merton problem $M_t(X_t)$ defined in (4), and \hat{U}' and M'_t are the derivatives with respect to the wealth-argument. Kramkov and Sirbu (2006) directly adopt (71) as the definition of the marginal utility price for European claims, which we also adapt to the case of American options.

Definition 13 *The marginal utility price process $(h_t)_{0 \leq t \leq T}$ for an American option with payoff process $(g_t)_{0 \leq t \leq T}$ is defined as*

$$h_t = \frac{\text{ess sup}_{\tau \in \mathcal{T}_{t,T}} \mathbb{E} \left\{ M'_\tau(\hat{X}_\tau^*) g_\tau \mid \mathcal{F}_t \right\}}{M'_t(X_t)}, \quad (72)$$

where $M_t(X_t)$ is given in (4).

Among others, one important question is under what conditions does the marginal utility price become independent of the investor's wealth. In the classical setting for options without early exercise, wealth-independence of marginal utility prices is very rare. In fact, Kramkov and Sirbu (2006) show that only exponential and power utilities yield wealth-independent marginal utility prices for any payoff and in any financial market.

5.2 The Marginal Forward Indifference Price Formula

Following the definition of the classical marginal indifference price, we introduce the marginal forward indifference price for our model. Henceforth, we will give the definitions and results based on the Itô diffusion market settings described in Section 2, where the discounted stock price S follows (2) and the option holder's trading wealth X_t follows (3).

Definition 14 *Let $U_t(x) = u(x, A_t)$, with $A_t = \int_0^t \lambda_s^2 ds$, be the investor's forward performance process, and assume X^* is the optimal wealth process in (15) (cf. Theorem 3). The*

marginal forward indifference price process $(\tilde{p}_t)_{0 \leq t \leq T}$ for an American option with an \mathcal{F}_t -adapted bounded payoff process $(g_t)_{0 \leq t \leq T}$ is defined as

$$\tilde{p}_t = \frac{\text{ess sup}_{\tau \in \mathcal{T}_{t,T}} \mathbb{E} \{u_x(X_\tau^*, A_\tau) g_\tau | \mathcal{F}_t\}}{u_x(X_t^*, A_t)}. \quad (73)$$

At first glance, the marginal forward indifference price in (73) might depend on the holder's risk preferences and wealth. However, as the next result shows, under a time-monotone forward performance the marginal forward indifference price is *independent* of both of these inputs, and is simply given as the expected discounted payoff under the MMM, regardless of the investor's forward performance criterion.

Theorem 15 *The marginal forward indifference price of an American option with payoff process $(g_t)_{0 \leq t \leq T}$ is given by*

$$\tilde{p}_t = \text{ess sup}_{\tau \in \mathcal{T}_{t,T}} \mathbb{E}^{Q^0} \{g_\tau | \mathcal{F}_t\}, \quad (74)$$

where Q^0 is the MMM. Consequently, \tilde{p}_t is independent of both the holder's wealth and his forward performance criterion.

Proof. Comparing (73) and (74), we observe that it is sufficient to show that

$$\frac{u_x(X_\tau^*, A_\tau)}{u_x(X_t^*, A_t)} = \exp \left(-\frac{1}{2} \int_t^\tau \lambda_s^2 ds - \int_t^\tau \lambda_s dW_s \right), \quad \tau \in \mathcal{T}_{t,T}. \quad (75)$$

Indeed, since λ is bounded, this leads to the desired measure change from the historical measure \mathbb{P} to the MMM Q^0 .

Applying Itô's formula to $u_x(X_t^*, A_t)$ and using the SDE (15) for X^* gives

$$\begin{aligned} du_x(X_t^*, A_t) &= \lambda_t^2 \left(u_{xt}(X_t^*, A_t) + R(X_t^*, A_t) u_{xx}(X_t^*, A_t) + \frac{R(X_t^*, A_t)^2}{2} u_{xxx}(X_t^*, A_t) \right) dt \\ &\quad + \lambda_t R(X_t^*, A_t) u_{xx}(X_t^*, A_t) dW_t. \end{aligned} \quad (76)$$

Next, we show that the drift vanishes. First, it follows from differentiating $u(x, t)$ in (11) that

$$u_{xt} = u_x - \frac{u_x^2 u_{xxx}}{2u_{xx}^2}.$$

Using this and the fact that $R(x, t) = -u_x(x, t)/u_{xx}(x, t)$ to (76), we see that the drift in (76) becomes zero. As a result, the SDE (76) simplifies to

$$\begin{aligned} du_x(X_t^*, A_t) &= \lambda_t R(X_t^*, A_t) u_{xx}(X_t^*, A_t) dW_t \\ &= -\lambda_t u_x(X_t^*, A_t) dW_t. \end{aligned}$$

This implies that the process $(u_x(X_t^*, A_t))_{t \geq 0}$ is given by the stochastic exponential representation in (75). Hence, by a change of measure, formula (74) follows. ■

Theorem 15 illustrates a crucial feature of the forward indifference pricing mechanism. If we consider that, in a general Itô diffusion market, different investors adopt different forward performances according to Theorem 3, then their marginal forward indifference prices for an American claim will necessarily be the same, regardless of their wealth and choices of forward performance. In particular, this is true for the stochastic volatility model in (22)-(23) and the basis risk model in (63)-(64). In contrast, the classical marginal utility price

for a general utility function is typically wealth and utility dependent (Kramkov and Sirbu, 2006, Theorem 7). In the basis risk model as a special case, Kramkov and Sirbu (2006) show that the marginal utility price is also found from pricing under the MMM, thus coinciding with the forward counterpart, even though they are derived from very different performance mechanisms.

6 Conclusions and Extensions

In summary, we have discussed the forward indifference valuation for American options in an incomplete model with a stochastic factor. We have applied it to value American options under stochastic volatility and model the early exercises of ESOs. The option holder's optimal hedging and exercising strategies are found from solving the underlying variational inequalities.

The forward indifference valuation mechanism is profoundly different from the one in the classical approach. This is best illustrated in Section 3, in which the exponential forward indifference price is expressed in terms of relative entropy minimization with respect to the MMM, rather than with respect to the MEMM, as is the case in the traditional setting. Lastly, we also introduced the marginal forward indifference price. In contrast to the classical marginal utility price, the marginal forward indifference price based on any time-monotone forward performance is independent of both the investor's wealth, and is given as the risk-neutral expectation under the MMM.

Several major challenges and interesting problems remain for future investigation. These include the existence and regularity results for the variational inequalities associated with the optimal forward performance and the forward indifference price. The nonlinearity of the variational inequalities also requires the development of efficient numerical schemes. Moreover, even though we have focused on the valuation of American options, it is important to examine its impact in the host of other applications where traditional utility valuation has been used, for example, credit derivatives (Leung et al., 2008; Jaimungal and Sigloch, 2010), volatility derivatives (Grasselli and Hurd, 2008), insurance products (Bayraktar and Ludkovski, 2009), and order book modeling (Avellaneda and Stoikov, 2008). In all of these, exponential utility is chosen for its convenient analytic properties. Forward performance provides a convenient tool to i) move away from exponential utility, and ii) remove the horizon dependence.

A Admissibility and Characterization of Time-Monotone Forward Performances

Musiela and Zariphopoulou (2010a) have shown that there exists a class of *admissible* initial conditions, $u_0(x)$, for which the time-monotone performance is well defined and the associated optimal portfolio process can be explicitly constructed. In this appendix, we highlight some of the main results relevant to our study.

The class of admissible initial conditions is given via a positive, finite Borel measure which is, in turn, linked with a space-time harmonic function (see (78) and (80) below). As in Musiela and Zariphopoulou (2010a), we define the set of measures $\mathcal{B}^+(\mathbb{R})$ by

$$\mathcal{B}^+(\mathbb{R}) = \left\{ \nu \in \mathcal{B}(\mathbb{R}) : \forall B \in \mathcal{B}, \nu(B) \geq 0 \text{ and } \int_{\mathbb{R}} e^{yx} \nu(dy) < \infty, x \in \mathbb{R} \right\}. \quad (77)$$

Proposition 16 (*Proposition 3 of Musiela and Zariphopoulou (2010a)*) (i) Let $\nu \in \mathcal{B}^+(\mathbb{R})$.

Then, the function h defined, for $(x, t) \in \mathbb{R} \times [0, +\infty)$, by

$$h(x, t) = \int_{\mathbb{R}} \frac{e^{yx - \frac{1}{2}y^2t} - 1}{y} \nu(dy) + C, \quad (78)$$

is a strictly increasing solution to the PDE:

$$h_t + \frac{1}{2}h_{xx} = 0. \quad (79)$$

(ii) Assume that h above is of full range for each $t \geq 0$, and let $h^{(-1)} : \mathbb{R} \times [0, +\infty) \rightarrow \mathbb{R}$ be its spatial inverse. Then, the function u defined by

$$u(x, t) = -\frac{1}{2} \int_0^t e^{-h^{(-1)}(x, s) + \frac{s}{2}} h_x \left(h^{(-1)}(x, s), s \right) ds + \int_0^x e^{-h^{(-1)}(z, 0)} dz, \quad (80)$$

for $(x, t) \in \mathbb{R} \times [0, +\infty)$, is an increasing and strictly concave solution of the PDE (11).

The above result yields a class of admissible initial data for a forward performance process. Precisely, a function $u_0 : \mathbb{R} \rightarrow \mathbb{R}$ is admissible, if it can be represented as

$$u_0(x) = \int_0^x e^{-h^{(-1)}(z, 0)} dz, \quad x \in \mathbb{R},$$

with

$$h(x, 0) = \int_{\mathbb{R}} \frac{e^{yx} - 1}{y} \nu(dy) + C,$$

for some constant C and $\nu \in \mathcal{B}^+(\mathbb{R})$. Moreover, once the measure ν is defined, the function h yields directly a dynamic preference function u satisfying (11).

The following result, taken from Musiela and Zariphopoulou (2010a), provides the explicit construction of the optimal portfolio and the optimal wealth process. In establishing this result, they rigorously proved the admissibility of the optimal portfolio π^* under an integrability condition on the measure ν given in (81) below.

Theorem 17 (Theorem 4 of Musiela and Zariphopoulou (2010a)) (i) Let h be a strictly increasing solution to (79), for $(x, t) \in \mathbb{R} \times [0, +\infty)$, and assume that the associated measure ν satisfies

$$\int_{\mathbb{R}} e^{yx + \frac{1}{2}y^2t} \nu(dy) < +\infty. \quad (81)$$

Let also A_t be as in (10) and introduce m_t , $t \geq 0$, as

$$m_t = \int_0^t \lambda_s dW_s.$$

Define the processes X_t^* and π_t^* by

$$X_t^* = h \left(h^{(-1)}(x, 0) + A_t + m_t, A_t \right) \quad (82)$$

and

$$\pi_t^* = h_x \left(h^{(-1)}(X_t^*, A_t), A_t \right) \frac{\lambda_t}{\sigma_t}, \quad (83)$$

for $t \geq 0$, $x \in \mathbb{R}$ with h as above and $h^{(-1)}$ standing for its spatial inverse. Then, the portfolio π_t^* is admissible and generates X_t^* , i.e.,

$$X_t^* = x + \int_0^t \sigma_s \pi_s^* (\lambda_s ds + dW_s). \quad (84)$$

(ii) Let u be the associated with h increasing and strictly concave solution to (11). Then, the process $u(X_t^*, A_t)$, $t \geq 0$, satisfies the SDE

$$du(X_t^*, A_t) = u_x(X_t^*, A_t) \sigma_t \pi_t^* dW_t, \quad (85)$$

with X_t^* and π_t^* as in (82) and (83).

(iii) Let $U_t(x)$, $t \geq 0$, $x \in \mathbb{R}$ be given by (12) with u_0 being an admissible initial condition. Then, the processes X_t^* and π_t^* are optimal.

From (14) and (80), it can be shown that the local risk tolerance function is given by

$$R(x, t) = h_x(h^{-1}(x, t), t), \quad (86)$$

with h as in (78). Since both $h(x, t)$ and $u(x, t)$ are completely characterized by the measure ν , the same holds for the local risk tolerance function $R(x, t)$ in (86). In Example 12 of Musiela and Zariphopoulou (2010a), it was shown that the measure linked to the parametric risk tolerance function $R(x, t; \alpha, \beta)$ in (17) is given by

$$\nu(dy) = \frac{\sqrt{\beta}}{2} \left(\delta_{\sqrt{\alpha}} + \delta_{-\sqrt{\alpha}} \right),$$

with $\delta_{\pm\sqrt{\alpha}}$ are Dirac measures at $\pm\sqrt{\alpha}$. Hence, it is clear that this measure satisfies the integrability condition (81) in Theorem 17. Finally, in view of (78), the associated space-time harmonic function is given by

$$h(x, t) = \sqrt{\frac{\beta}{\alpha}} e^{-\frac{1}{2}\alpha t} \sinh(\sqrt{\alpha}x).$$

Using this, the optimal portfolio and wealth processes are in turn explicitly constructed as in (83) and (84).

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