AN OPTIMAL MEAN-REVERSION TRADING RULE UNDER A MARKOV CHAIN MODEL

JINGZHI TIE AND QING ZHANG
Department of Mathematics
University of Georgia
Athens, GA 30602, USA

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ABSTRACT. This paper is concerned with a mean-reversion trading rule. In contrast to most market models treated in the literature, the underlying market is solely determined by a two-state Markov chain. The major advantage of such Markov chain model is its striking simplicity and yet its capability of capturing various market movements. The purpose of this paper is to study an optimal trading rule under such a model. The objective of the problem under consideration is to find a sequence stopping (buying and selling) times so as to maximize an expected return. Under some suitable conditions, explicit solutions to the associated HJ equations (variational inequalities) are obtained. The optimal stopping times are given in terms of a set of threshold levels. A verification theorem is provided to justify their optimality. Finally, a numerical example is provided to illustrate the results.

1. Introduction. Major market models treated in mathematical finance in recent years can be classified into two broad categories: Cox-Ross-Rubinstein’s binomial tree model (BTM) and Brownian motion based models. See related books by Hull [15], Elliott and Kopp [8], Fouque et al. [10], Karatzas and Shreve [17], and Musiela and Rutkowski [20] among others.

The BTM is widely used in option pricing due to its simplicity and yet clear advantage when pricing American type options. However, a main drawback of the BTM is its non-Markovian nature. The lack of Markovian property makes it difficult to work with mathematically, not to mention closed-form solutions. To preserve the BTM’s simplicity and enhance its mathematical tractability, a two-state Markov chain model was considered in Zhang [29]. The Markov chain model in [29] appears to be natural for not frequently traded securities such as illiquid stocks. Its capability of capturing this type of markets makes it preferable in related applications. In addition, it can be seen from Example 1 to follow that the Markov chain model is closely related to the traditional mean-reversion diffusion when the jump rates of the Markov chain are large. Related Markov chain based models can be found in Van der Hoek and Elliott [23] and Norberg [21]. Van der Hoek and Elliott introduced a stock price model based on stock dividend rates and a Markov chain noise. Norberg used a Markov chain to represent interest rate and considered a market model driven...
by a Markov chain. In particular, the market model in [21] resembles a GBM in which the ‘drift’ is approximated by the duration between jumps and the ‘diffusion’ is given in terms of jump times. An additional advantage of a Markov chain driven model is that its price is almost everywhere differentiable. Such differentiability is desirable in the optimal control type market analysis proposed by Barmish and Primbs [1]. In connection with dynamic programming problems, the corresponding Hamilton-Jacobi (HJ) equations are of the first order, which are easier to analyze than those under traditional Brownian motion based models.

Mean-reversion models are often used in financial markets to capture price movements that have the tendency to move towards an ‘equilibrium.’ There are many studies in connection with mean-reversion stock returns; see e.g., Cowles and Jones [5], Fama and French [9], and Gallagher and Taylor [11] among others. In addition to equity markets, mean-reversion models are used for stochastic interest rates (Vasicek [24] and Hull [15]); stochastic volatility (Hafner and Herwartz [14]); and energy markets (Blanco and Soronow [2]). See also related results in option pricing with a mean-reversion asset by Bos, Ware and Pavlov [3].

Mathematical trading rules have been studied for many years. For example, Zhang [28] considered a selling rule determined by two threshold levels, a target price and a stop-loss limit. Such optimal threshold levels are obtained by solving a set of two-point boundary value problems. Guo and Zhang [13] studied the optimal selling rule under a model with regime switching. Using a smooth-fit technique, they obtained the optimal threshold levels by solving a set of algebraic equations. These papers are concerned with the selling side of trading in which the underlying price models are of GBM type. Recently, Dai et al. [7] developed a trend following rule based on a conditional probability indicator. They showed that the optimal trading rule can be determined by two threshold curves which can be obtained by solving the associated HJ equations. Similar idea was developed following a confidence interval approach by Iwarere and Barmish [16]. In addition, Merhi and Zervos [18] studied an investment capacity expansion/reduction problem following a dynamic programming approach under a geometric Brownian motion market model. In connection with mean-reversion trading, Zhang and Zhang [27] obtained a buy-low and sell-high policy by charactering the ‘low’ and ‘high’ levels in terms of two threshold levels. Further development along this line can be found in pairs trading in Song and Zhang [22]. Under a mean-reversion model, a pair of stocks can be traded simultaneously, when their price divergence exceeds a predetermined level, to bet on their eventual convergence. More details in connection with pairs trading and extensive empirical market tests can be found in Gatev et al. [12] and references therein.

To take advantage of many new features of Markov chain models and explore related mean-reversion markets, it is the purpose of this paper to study the corresponding trading strategies. The objective is to buy and sell the mean-reversion security to maximize a reward function. A fixed (commission or slippage) cost will be imposed to each transaction. We study the problem following a dynamic programming approach and establish the associated HJ equations for the value functions. We show that the corresponding optimal stopping (buying and selling) times can be determined by four threshold levels depending on market states. These key levels can be obtained by solving a set of algebraic like equations. In solving the associated HJ equations, hypergeometric series arise naturally in the analysis. Various boundary conditions and convexity conditions of hypergeometric functions
are involved extensively. We provide a set of sufficient conditions that guarantee the optimality of the trading rules. Finally, to illustrate the results, we present a market backtesting example with the daily closing prices of Dow Jones Industrial Average from 1961 to 1980.

The main contributions of this paper include: (1) Introduction of a new mean-reversion model driven by a two-state Markov chain. Such model is very simple in structure and yet powerful enough to capture many important market features. (2) Development of mean-reversion trading strategies that are simple to implement. The corresponding optimal stopping problem is solved using a smooth-fit technique and hypergeometric analysis is involved in a substantial way.

This paper is organized as follows. In §2, we formulate the mean-reversion trading problem under consideration. In §3, we study preliminary properties of the value functions. In §4, we consider the associate HJ equations and their solutions. Then in §5, we discuss additional inequalities including the variational inequalities arising from the HJ equations and related convexity conditions. In §6, we give a verification theorem under suitable conditions. A numerical example is considered in §7. Several technical lemmas are postponed and provided in Appendix.

2. Problem formulation. Let \( \{\alpha_t : t \geq 0\} \) denote a two-state Markov chain with state space \( \mathcal{M} = \{1, 2\} \) and the generator \( Q = \begin{pmatrix} -\lambda_1 & \lambda_1 \\ \lambda_2 & -\lambda_2 \end{pmatrix} \). Here \( \lambda_1 \) and \( \lambda_2 \) are positive.

Let \( S_t \) denote the stock price (or a function of the price) at time \( t \) given by the equation

\[
\frac{dS_t}{dt} = a(b - S_t) + f(\alpha_t), \quad t \geq 0, \tag{1}
\]

where \( a > 0 \) is the rate of reversion and \( b \) the equilibrium. Here \( f(1) = f_1 > 0 \) represents the uptick return rate and \( f(2) = f_2 < 0 \) the downtick return rate.

**Example 2.1. (Convergence to a Mean-Reversion Diffusion).** In this example, we present a simple Markov chain model and demonstrate how it approaches the corresponding mean-reversion diffusion. Given \( \varepsilon > 0 \), we consider \( f_1 = \sigma/\sqrt{\varepsilon}, f_2 = -\sigma/\sqrt{\varepsilon}, \lambda_1 = \lambda_2 = 1/\varepsilon \). Using the asymptotic normality given in Yin and Zhang [26, Theorem 5.9], we can show that the solution to (1) \( S_t = S^\varepsilon_t \) converges weakly to the solution of \( dS_t = a(b - S_t)dt + \sigma dW_t \), where \( W_t \) is a standard Brownian motion.

In particular, taking \( a = 1, b = 2, \sigma = 0.5, \) and \( \varepsilon = 0.1 \), we generate the Monte Carlo sample paths of \( (S^\varepsilon_t, \alpha^\varepsilon_t) \). One sample is given in (a) of Figure 1. Similarly, we vary \( \varepsilon \) and plot the corresponding sample paths in (b) and (c) of Figure 1. It is clear from these pictures that as \( \varepsilon \) gets smaller and smaller, the fluctuation of \( \alpha_t \) is more and more rapidly and the corresponding \( S^\varepsilon_t \) approaches to a mean-reversion diffusion.

**Remark 2.1.** The main advantage of our model is its simplicity and flexibility in capturing various market conditions. For example, in a typical sideways (trendless) market, the price range can be precisely defined. In our model, such ‘price band’ arises naturally. A candidate for the band can be given by the interval \([b + f_2/a, b + f_1/a]\).

We consider the state process \( X_t = S_t - b \). Then \( X_t \) satisfies

\[
\frac{dX_t}{dt} = -aX_t + f(\alpha_t), \quad t \geq 0, \tag{2}
\]
with initial vector \((X_0, \alpha_0) = (x, \alpha)\). Let \(\mathcal{I}_0 = [f_2/a, f_1/a]\). Then \(X_t \in \mathcal{I}_0\) for all \(t \geq 0\) if \(X_0 \in \mathcal{I}_0\).

Let \(\mathcal{F}_t = \{X_r : r \leq t\}\) denote the filtration generated by \(X_t\). Note that \(\alpha_t\) is observable and \(\mathcal{F}_t = \{\alpha_r : r \leq t\}\). Let

\[
0 \leq \tau_1^0 \leq \tau_1^1 \leq \tau_2^0 \leq \tau_2^1 \leq \cdots
\]

(3)
denote a sequence of stopping times with respect to \( \{ F_t \} \). A buying decision is made at \( \tau^b_n \) and a selling decision at \( \tau^s_n \), \( n = 1, 2, \ldots \).

We consider the case that the net position at any time can be either long with one share of the stock or flat with no stock position. Let \( i = 0, 1 \) denote the initial net position. If the initial net position is long \((i = 1)\), then one should sell the stock before acquiring any future shares. The corresponding sequence of stopping times is denoted by \( \Lambda_1 = (\tau^b_1, \tau^b_2, \tau^s_2, \tau^b_3, \ldots) \). Likewise, if the initial net position is flat \((i = 0)\), then one should start to buy a share of the stock. The corresponding sequence of stopping times is denoted by \( \Lambda_0 = (\tau^b_1, \tau^s_1, \tau^s_2, \ldots) \).

Let \( K > 0 \) denote the fixed transaction cost (e.g., slippage and/or commission). Given the initial state vector \((X_0, \alpha_0) = (x, \alpha)\), the initial net position \( i = 0, 1 \), and the decision sequences \( (\Lambda_0, \Lambda_1) \), we consider the corresponding reward functions

\[
J_i(x, \alpha, \Lambda_i) = \begin{cases} 
E \left\{ \sum_{n=1}^{\infty} e^{-\rho \tau^b_n} (X_{\tau^b_n} - K) - e^{-\rho \tau^s_n} (X_{\tau^s_n} + K) \right\}, & \text{if } i = 0, \\
E \left\{ e^{-\rho \tau^b_1} (X_{\tau^b_1} - K) + \sum_{n=2}^{\infty} e^{-\rho \tau^b_n} (X_{\tau^b_n} - K) - e^{-\rho \tau^s_n} (X_{\tau^s_n} + K) \right\}, & \text{if } i = 1,
\end{cases}
\]

(4)

where \( \rho > 0 \) is a given discount factor.

In this paper, given random variables \( x_n \), the term \( E \{ \sum_{n=1}^{\infty} x_n \} \) is interpreted as

\[
\lim \sup_{N \to \infty} E \sum_{n=1}^{N} x_n.
\]

For \( i = 0, 1 \), let \( V_i(x, \alpha) \) denote the value functions with the initial vector \((X_0, \alpha_0) = (x, \alpha)\) and initial net positions \( i = 0, 1 \). That is,

\[
V_i(x, \alpha) = \sup_{\Lambda_i} J_i(x, \alpha, \Lambda_i).
\]

(5)

It follows from (2) that \( X_t = xe^{-at} + e^{-at} \int_0^t e^{ar} f(\alpha_r) dr \). Therefore, \( J_i(x, \alpha, \Lambda_i) \) is linear in \( x \) and \( V_i(x, \alpha) \) is convex in \( x \) for fixed \( i = 0, 1 \) and \( \alpha = 1, 2 \).

In practice, the transaction cost \( K > 0 \) is typically small when compared to all other parameters. Here we assume it is smaller than both \( (f_1/a) \) and \( (-f_2/a) \). In addition, both \( \lambda_1 \) and \( \lambda_2 \) are large numbers relative to \( a \). So we also assume \( \lambda_1 > a \) and \( \lambda_2 > a \).

We summarize conditions to be imposed in this paper:

- \( (A1) \) \( f_1 > 0 \) and \( f_2 < 0 \);
- \( (A2) \) \( K < \min \{ f_1/a, |f_2|/a \} \);
- \( (A3) \) \( \lambda_1 > a \) and \( \lambda_2 > a \).

Note that in this paper the stock price \( X_t \) is differentiable and the value of \( \alpha_t \) can be given in terms of the derivative of \( X_t \) with respect to \( t \).

3. Properties of the value functions.

**Lemma 3.1.** The following inequalities hold.

(a) \( 0 \leq V_0(x, \alpha) \leq \left( \frac{\rho + 2a}{\rho a} \right) \max \{ f_1, |f_2| \} \), for all \((x, \alpha) \in I_0 \times \mathcal{M} \).
(b) \(-K \leq V_0(x, \alpha) - V_1(x, \alpha) + x \leq K\), for all \((x, \alpha) \in \mathcal{I}_0 \times \mathcal{M}\). Therefore, \(V_1(x, \alpha)\) is also bounded on \(\mathcal{I}_0 \times \mathcal{M}\).

**Proof.** It is clear that \(V_0(x, \alpha) \geq 0\). To show it is bounded from above, we first note that
\[
\frac{d(e^{-\rho t}X_t)}{dt} = e^{-\rho t}(-\rho + a)X_t + f(\alpha_t).
\]
Given \(\Lambda_0\), integrate both sides over \([\tau^*_n, \tau^*_n]\) to obtain
\[
e^{-\rho \tau^*_n}X_{\tau^*_n} - e^{-\rho \tau^*_n}X_{\tau^*_n} = \int_{\tau^*_n}^{\tau^*_n} e^{-at}(-\rho + a)X_t + f(\alpha_t) dt.
\]
It follows that, for \((x, \alpha) \in \mathcal{I}_0 \times \mathcal{M},
\]
\[
J_0(x, \alpha, \Lambda_0) = E \sum_{n=1}^{\infty} \left[ e^{-\rho \tau^*_n}X_{\tau^*_n} - e^{-\rho \tau^*_n}X_{\tau^*_n} - K \right] \\
\leq E \sum_{n=1}^{\infty} \left[ e^{-\rho \tau^*_n}X_{\tau^*_n} - e^{-\rho \tau^*_n}X_{\tau^*_n} \right] \\
\leq E \sum_{n=1}^{\infty} \int_{\tau^*_n}^{\tau^*_n} e^{-at}(-\rho + a)X_t + f(\alpha_t) dt \\
\leq E \int_{0}^{\infty} e^{-at}((\rho + a)|X_t| + |f(\alpha_t)|) dt \\
\leq \left( \frac{\rho + 2a}{\rho a} \right) \max\{f_1, |f_2|\}.
\]
This implies (a).

To show that \(V_0(x, \alpha) - V_1(x, \alpha) + x \leq K\), or \(V_1(x, \alpha) \geq V_0(x, \alpha) + x - K\), we note that, for a given \(\Lambda_1\) with \(\tau^*_1 = 0,
\]
\[
V_1(x, \alpha) \geq J_1(x, \alpha, \Lambda_1) + x - K.
\]
Since the rest stopping times in \(\Lambda_1\) are arbitrary, it follows that \(V_1(x, \alpha) \geq V_0(x, \alpha) + x - K\). Similarly, we can show the second inequality in (b). \(\square\)

4. HJ equations. Let \(\mathcal{A}\) denote the generator of \((X_t, \alpha_t)\), i.e., for any differentiable functions \(h(x, i), i = 1, 2,\)
\[
\left\{ \begin{array}{l}
\mathcal{A}h(x, 1) = (-ax + f_1)h'(x, 1) + \lambda_1(h(x, 2) - h(x, 1)), \\
\mathcal{A}h(x, 2) = (-ax + f_2)f_2h'(x, 2) + \lambda_2(h(x, 1) - h(x, 2)),
\end{array} \right.
\]
where \(h'\) denotes the derivative of \(h\) with respect to \(x\). The associated HJ equations should have the form:
\[
\min\{\rho v_0(x, \alpha) - \mathcal{A}v_0(x, \alpha), v_0(x, \alpha) - v_1(x, \alpha) + x + K\} = 0,
\]
\[
\min\{\rho v_1(x, \alpha) - \mathcal{A}v_1(x, \alpha), v_1(x, \alpha) - v_0(x, \alpha) - x + K\} = 0,
\]
for \(\alpha = 1, 2,\)

In this paper, our goal is to find the value functions by solving these HJ equations with all value function properties satisfied. Then we proceed to show that such functions \(v_i(x, \alpha)\) are equal to the value functions.
4.1. **Solving** \((\rho - \mathcal{A})v_i(x, \alpha) = 0\). To solve these HJ equations, for each fixed \(i = 0, 1\), we consider equations when \(\rho v_i(x, \alpha) - \mathcal{A}v_i(x, \alpha) = 0, \alpha = 1, 2\). Using the generator \(\mathcal{A}\), we can write

\[
\begin{align*}
(\rho + \lambda_1)v_i(x, 1) &= (-ax + f_1)v'_i(x, 1) + \lambda_1 v_i(x, 2), \\
(\rho + \lambda_2)v_i(x, 2) &= (-ax + f_2)v'_i(x, 2) + \lambda_2 v_i(x, 1).
\end{align*}
\] (7)

For each fixed \(i = 0, 1\) and \(\alpha = 1, 2\), let \(y_\alpha(x) = v_i(x, \alpha)\). Then, using the first equation, we can write \(y_2\) in terms of \(y_1\):

\[
y_2(x) = \frac{1}{\lambda_1}[(\rho + \lambda_1)y_1(x) + (ax - f_1)y'_1(x)].
\]

Its derivative with respect to \(x\) is given by

\[
y'_2(x) = \frac{1}{\lambda_1}[(\rho + \lambda_1 + a)y'_1(x) + (ax - f_1)y''_1(x)].
\]

Substitute these into the second equation in (7) to obtain

\[
(ax - f_1)(ax - f_2)y''_1(x) + [(\rho + \lambda_2)(ax - f_1) + (\rho + \lambda_1 + a)(ax - f_2)]y'_1(x) + \rho(\rho + \lambda_1 + \lambda_2)y_1(x) = 0.
\]

To simplify this equation, let

\[
\xi = \frac{ax - f_2}{f_1 - f_2}
\]

and \(u(\xi) = y_1(x)\). Then, it follows that

\[
ax - f_2 = (f_1 - f_2)\xi \quad \text{and} \quad ax - f_1 = (f_1 - f_2)(\xi - 1).
\]

Moreover, applying the chain rule to obtain

\[
y'_1(x) = \left(\frac{a}{f_1 - f_2}\right)u'(\xi) \quad \text{and} \quad y''_1(x) = \left(\frac{a}{f_1 - f_2}\right)^2 u''(\xi).
\]

This reduces the equation for \(y_1(x)\) into an equation for \(u(\xi)\) as

\[
a^2\xi(\xi - 1)u''(\xi) + a[(\rho + \lambda_2)(t - 1) + (\rho + \lambda_1 + a)t]u'(\xi) + \rho(\rho + \lambda_1 + \lambda_2)u(\xi) = 0.
\]

Next, we introduce the additional parameters

\[
\gamma_1 = \frac{\rho}{a}, \quad \gamma_2 = \frac{\rho + \lambda_1 + \lambda_2}{a}, \quad \gamma_3 = \frac{\rho + \lambda_2}{a}.
\]

Then, we can write the above differential equation in terms of \((\gamma_1, \gamma_2, \gamma_3)\) as

\[
\xi(1 - \xi)u''(\xi) + [\gamma_3 - (\gamma_1 + \gamma_2)\xi]u'(\xi) - \gamma_1 \gamma_2 u(\xi) = 0.
\]

(8)

This is exactly the classical hypergeometric equation. Related properties of hypergeometric functions can be found in [19] and [25].

For any real numbers \(\eta_i, i = 1, 2, 3\), let

\[
F(\eta_1, \eta_2; \eta_3, \xi) = \sum_{n=0}^{\infty} \frac{(\eta_1)_n(\eta_2)_n}{n!(\eta_3)_n} \xi^n,
\]

where

\[
(\eta)_0 = 1 \quad \text{and} \quad (\eta)_n = \eta(\eta + 1) \cdots (\eta + n - 1) = \frac{\Gamma(\eta + n)}{\Gamma(\eta)},
\]

for any \(\eta = \eta_i\). Then, for \(0 < \xi < 1\), two independent solutions of (8) can be given by

\[
F\left(\frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_2}{a}, \xi\right) \quad \text{and} \quad F\left(\frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_2 + a}{a}, 1 - \xi\right).
\]
Let
\[
F_1(x) = F\left(\frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_2}{a}, \frac{ax - f_2}{f_1 - f_2}\right),
\]
\[
\bar{F}_1(x) = F\left(\frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_2 + a}{a}, 1 - \frac{ax - f_2}{f_1 - f_2}\right).
\]  \tag{9}

We consider these solutions over a neighborhood in \(I_0\) containing the lower end \(f_2/a\). Then any solution over this interval can be written as a linear combination of \(F_1\) and \(\bar{F}_1\), i.e., for some constants \(C_1\) and \(\bar{C}_1\), \(v_i(x, 1) = C_1 F_1(x) + \bar{C}_1 \bar{F}_1(x),\ i = 0, 1\). In particular, we need this solution to be bounded near \(f_2/a\). This requires \(\bar{C}_1 = 0\) because \(\bar{F}_1(x) \to \infty\) as \(x \to f_2/a\) (see Lemma 8.1 in Appendix).

Therefore, on the neighborhood of \(I_0\) containing \(f_2/a\) we can assume that \(v_1(x, 1) = C_1 F_1(x)\). Using this solution, we can write \(v_1(x, 2)\) in terms of \(F_1(x)\):
\[
v_1(x, 2) = \frac{C_1}{\lambda_1}[(\rho + \lambda_1)F_1(x) + (ax - f_1)F_1'(x) := C_1 G_1(x). \tag{10}
\]

Alternatively, we can use the second equation in (7) and write \(y_1\) in terms of \(y_2\):
\[
y_1(x) = \frac{1}{\lambda_2}[(\rho + \lambda_2)y_2(x) + (ax - f_2)y_2'(x)]
\]
and its derivative in terms of \(y_2\) and \(y_2''\)
\[
y_1'(x) = \frac{1}{\lambda_2}[(\rho + \lambda_2 + a)y_2(x) + (ax - f_2)y_2''(x)].
\]

Substituting these into the first equation in (7) to obtain
\[
(ax - f_1)(ax - f_2)y_2''(x) + [(\rho + \lambda_1)(ax - f_2) + (\rho + \lambda_2 + a)(ax - f_1)]y_1(x) + \rho(\rho + \lambda_1 + \lambda_2)y_2(x) = 0.
\]

Similarly, let \(w(\xi) = y_2(x)\) with
\[
\xi = \frac{f_1 - ax}{f_1 - f_2},
\]

Then, we can write the above differential equation in terms of \(w(\xi)\):
\[
\xi(1 - \xi)w''(\xi) + [\gamma_3 - (\gamma_1 + \gamma_2 + 1)\xi]\xi w'(\xi) - \gamma_1 \gamma_2 w(\xi) = 0,
\]
with \(\gamma_3 = (\rho + \lambda_1)/a\). Its two independent solutions can be given by
\[
F\left(\frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_1}{a}, \xi\right) \text{ and } F\left(\frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_1 + a}{a}, 1 - \xi\right).
\]

Let
\[
F_2(x) = F\left(\frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_1}{a}, \frac{f_1 - ax}{f_1 - f_2}\right),
\]
\[
\bar{F}_2(x) = F\left(\frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_2 + a}{a}, 1 - \frac{f_1 - ax}{f_1 - f_2}\right). \tag{11}
\]

Similarly, we consider these solutions over a neighborhood in \(I_0\) containing the upper end \(f_1/a\). Again, any solution can be written as a linear combination of \(F_2\) and \(\bar{F}_2\), i.e., for some constants \(C_2\) and \(\bar{C}_2\), \(v_i(x, 2) = C_2 F_2(x) + \bar{C}_2 \bar{F}_2(x),\ i = 0, 1\). We now need this solution to be bounded near \(f_1/a\), which implies \(\bar{C}_2 = 0\) because \(\bar{F}_2(x) \to \infty\) as \(x \to f_1/a\).
shown in Lemma 8.2 (Appendix) that the corresponding equalities in the HJ equations in (6) are marked in Figure 2.

Lemma 4.1. The solutions of \((\rho - A) v_i (x, \alpha) = 0\) can be given as

\[ v_0(x, 1) = C_2 G_1(x), \quad v_0(x, 2) = C_2 F_2(x), \quad v_1(x, 1) = C_1 F_1(x), \quad v_1(x, 2) = C_1 G_1(x), \]

where \(F_1, F_2, G_1, \) and \(G_2\) are defined in (9), (11), (10), and (12), respectively.

4.2. Order of threshold levels. If \(\alpha_t = 1\), let \(b_1\) denote the buying threshold (to buy when \(X_t < b_1\)) and \(s_1\) the selling threshold (to sell when \(X_t > s_1\)), respectively. Likewise, if \(\alpha_t = 2\), let \(b_2\) and \(s_2\) denote the corresponding buying and selling thresholds, respectively.

In the purely selling case, it is shown in [29] that \(s_1 > s_2\). Intuitively, \(b_1\) should be greater than \(b_2\) as well.

In addition, in this paper, we consider the case when \(b_1 < s_2\).

The opposite inequality \(b_1 > s_2\) means to buy when \(\alpha_t = 1\) and \(X_t < b_1\) and sell as soon as \(\alpha_t\) jumps to 2 and \(X_t > s_2\). This case rarely arises in practice because the jump rates \(\lambda_1\) and \(\lambda_2\) are typically large so that \(\alpha_t\) switches between 1 and 2 frequently.

In view of these, we consider the threshold levels having the following order

\[ \frac{f_2}{a} < b_2 < b_1 < s_2 < s_1 < \frac{f_1}{a}. \]

The corresponding equalities in the HJ equations in (6) are marked in Figure 2.

Using convexity of the value functions and variational inequalities in (6), it is shown in Lemma 8.2 (Appendix) that

\[ b_2 = \frac{f_2 - \rho K}{\rho + a} \quad \text{and} \quad s_1 = \frac{f_1 + \rho K}{\rho + a}. \]

It is easy to check, under Assumption (A2), that \(b_2\) and \(s_1\) given above indeed satisfy the inequalities \(b_2 > f_2/a\) and \(s_1 < f_1/a\).

4.3. Solving \((\rho - A) v_1 (x, 1) = 0\) with \(v_1(x, 2) = v_0(x, 2) + x - K\) and \((\rho - A) v_0 (x, 2) = 0\) with \(v_0(x, 1) = v_1(x, 1) - x - K\). For \(x \in I_0\), let

\[ g_1(x) = \left( \frac{ax - f_1}{as_1 - f_1} \right)^{s_1 + \lambda_1} \quad \text{and} \quad g_2(x) = \left( \frac{ab_2 - f_2}{ax - f_2} \right)^{s_2 + \lambda_2}. \]
Next, we solve the HJ equations on \([s_2, s_1]\). Note that on this interval, \(v_0(x, 1) = C_2 g_2(x)\), \(v_0(x, 2) = C_2 F_2(x)\), and \(v_1(x, 2) = v_0(x, 2) + x - K = C_2 F_2(x) + x - K\). To solve \(\rho v_1(x, 1) = A v_1(x, 1)\) on this interval, we write it as

\[(ax - f_1)v'_1(x, 1) + (\rho + \lambda_1)v_1(x, 1) = \lambda_1 v_1(x, 2)\]

Differentiate \((1/g_1(x))v_1(x, 1)\) and then integrate from \(s_1\) to \(x\) to obtain

\[v_1(x, 1) = v_1(s_1, 1) g_1(x) - \lambda_1 (ax - f_1)^{-\frac{\rho + \lambda_1}{a}} \int_{s_1}^{x} (f_1 - as)^{-\frac{\rho + \lambda_1}{a}} v_1(s, 2) ds\]

Recall that \(v_1(x, 2) = C_2 F_2(x) + x - K\). We write

\[v_1(x, 1) = g_1(x) A + k_1(x) C_2 + k_2(x)\]

where \(A = v_1(s_1, 1)\) and

\[
\begin{align*}
k_1(x) &= -\lambda_1 (f_1 - ax)^{-\frac{\rho + \lambda_1}{a}} \int_{s_1}^{x} (f_1 - as)^{-\frac{\rho + \lambda_1}{a}} F_2(s) ds, \\
k_2(x) &= -\lambda_1 (f_1 - ax)^{-\frac{\rho + \lambda_1}{a}} \int_{s_1}^{x} (f_1 - as)^{-\frac{\rho + \lambda_1}{a}} (s - K) ds.
\end{align*}
\]

Similarly, we solve the HJ equations on \([b_2, b_1]\). Note that on this interval, \(v_1(x, 1) = C_1 f_1(x)\), \(v_1(x, 2) = C_1 g_1(x)\), and \(v_0(x, 1) = v_1(x, 1) - x - K = C_1 F_1(x) - x - K\). To solve \(\rho v_0(x, 2) = A v_0(x, 2)\) on this interval, we first write it as

\[(ax - f_2)v'_0(x, 2) + (\rho + \lambda_2)v_0(x, 2) = \lambda_2 v_0(x, 1)\]

Differentiate \((1/g_2(x))v_0(x, 2)\) and then integrate over \([b_2, x]\) to obtain

\[v_0(x, 2) = v_0(b_2, 2) g_2(x) + \lambda_2 (ax - f_2)^{-\frac{\rho + \lambda_2}{a}} \int_{b_2}^{x} (as - f_2)^{-\frac{\rho + \lambda_2}{a}} v_0(s, 1) ds\]

Recall that \(v_0(x, 1) = C_1 f_1(x) - x - K\). We write

\[v_0(x, 2) = g_2(x) B + h_1(x) C_1 + h_2(x)\]

where \(B = v_0(b_2, 2)\) and

\[
\begin{align*}
h_1(x) &= \lambda_2 (ax - f_2)^{-\frac{\rho + \lambda_2}{a}} \int_{b_2}^{x} (as - f_2)^{-\frac{\rho + \lambda_2}{a}} F_1(s) ds, \\
h_2(x) &= -\lambda_2 (ax - f_2)^{-\frac{\rho + \lambda_2}{a}} \int_{b_2}^{x} (as - f_2)^{-\frac{\rho + \lambda_2}{a}} (s + K) ds.
\end{align*}
\]

Using the power series form of \(F_1(x) = \sum_{n=0}^{\infty} \frac{1}{f_1 - f_2} \left(\frac{ax-f_2}{f_1-f_2}\right)^n\), we can write

\[h_1(x) = \lambda_2 \sum_{n=0}^{\infty} \frac{p_n}{\rho + \lambda_2 + an} \left[\left(\frac{ax-f_2}{f_1-f_2}\right)^n - g_2(x) \left(\frac{ab_2-f_2}{f_1-f_2}\right)^n\right]\]

Similarly, we have

\[h_2(x) = -\lambda_2 \frac{1}{a} \left[\frac{1}{\rho + \lambda_2 + a} \left(\frac{(ax-f_2) - (ab_2-f_2) g_2(x)}{f_1-f_2}\right) + \frac{f_2 + aK}{\rho + \lambda_2} (1 - g_2(x))\right].\]

Likewise, write \(F_2(x) = \sum_{n=0}^{\infty} q_n \left(\frac{f_1-ax}{f_1-f_2}\right)^n\) to obtain

\[k_1(x) = -\lambda_1 \sum_{n=0}^{\infty} \frac{q_n}{\rho + \lambda_1 + an} \left[g_1(x) \left(\frac{f_1-as_1}{f_1-f_2}\right)^n - \left(\frac{f_1-ax}{f_1-f_2}\right)^n\right]\]
and

\[k_2(x) = \frac{\lambda_1}{a} \left[ -\frac{1}{\rho + \lambda_1 + a} ((f_1 - ax) - (f_1 - as_1)g_1(x)) + \frac{f_1 - aK}{\rho + \lambda_1} (1 - g_1(x)) \right].\]

4.4. **Smooth-fit conditions.** Note that the convexity of \(v_i(x, \alpha)\) in \(x\) on \(I_0\) implies that they are continuous in the interior of \(I_0\). The continuity of these functions at the threshold levels leads to the following conditions:

\[
\begin{align*}
&x = b_2 : \quad C_1G_1(b_2) - b_2 - K = g_2(b_2)B + h_1(b_2)C_1 + h_2(b_2); \\
&x = b_1 : \quad C_1F_1(b_1) - b_1 - K = C_2G_2(b_1), \\
&x = s_2 : \quad C_1G_1(s_2) = C_2F_2(s_2) + s_2 - K, \\
&x = s_1 : \quad C_2G_2(s_1) + s_1 - K = g_1(s_1)A + k_1(s_1)C_2 + k_2(s_2),
\end{align*}
\]

(13)

Recall that \(b_2 = (f_2 - \rho K)/(\rho + a)\) and \(s_1 = (f_1 + \rho K)/(\rho + a)\). Using the first and last equations in (13), we can write

\[
\begin{align*}
&\begin{pmatrix} B = (G_1(b_2) - h_1(b_2)) \quad C_1 - \frac{b_2 + K + h_2(b_2)}{g_2(b_2)} \quad =: B_1C_1 + B_2 \\
&\begin{pmatrix} A = (G_2(s_1) - k_1(s_1)) \quad C_2 + \frac{s_1 - K - k_2(s_1)}{g_1(s_1)} \quad =: A_1C_2 + A_2. \\
\end{pmatrix}
\end{align*}
\]

Then, we can write the second and the third equations in terms of \(C_1\) and \(C_2\):

\[
\begin{pmatrix} F_1(b_1) \\
\begin{pmatrix} C_1 \quad C_2 \quad = \begin{pmatrix} b_1 + K \\
\begin{pmatrix} g_2(b_1)B_1 + h_1(b_1) \quad F_2(b_1) \quad -g_2(b_1)B_2 - h_2(b_1) \quad .
\end{pmatrix}
\end{pmatrix}
\end{pmatrix}
\]

Similarly, we can write the fourth and the fifth equations as follows:

\[
\begin{pmatrix} F_1(s_2) \\
\begin{pmatrix} C_1 \quad C_2 \quad = \begin{pmatrix} s_2 - K \\
\begin{pmatrix} g_2(s_2)A_1 + k_1(s_2) \quad F_2(s_2) \quad -g_2(s_2)A_2 + k_2(s_2) \quad .
\end{pmatrix}
\end{pmatrix}
\end{pmatrix}
\]

If the above \(2 \times 2\) matrices are invertible, then we can eliminate \(C_1\) and \(C_2\) and obtain

\[
\begin{pmatrix} F_1(b_1) \\
\begin{pmatrix} G_1(s_2) \quad F_2(s_2) \quad = \begin{pmatrix} b_1 + K \\
\begin{pmatrix} g_2(b_1)B_1 + h_1(b_1) \quad F_2(b_1) \quad -g_2(b_1)B_2 - h_2(b_1) \quad .
\end{pmatrix}
\end{pmatrix}
\end{pmatrix}
\]

(14)

The solutions to the HJ equations (6) should have the form:

\[
\begin{align*}
&v_0(x, 1) = \begin{cases} C_1F_1(x) - x - K & \text{if } f_2/a \leq x \leq b_1, \\
C_2G_2(x) & \text{if } b_1 < x \leq f_1/a, \\
C_1G_1(x) - x - K & \text{if } f_2/a \leq x \leq b_2, \\
C_2F_2(x) & \text{if } b_1 < x \leq f_1/a, \\
C_1F_1(x) & \text{if } f_2/a \leq x \leq s_2, \\
C_2G_2(x) + x - K & \text{if } s_1 < x \leq f_1/a, \\
C_1G_1(x) & \text{if } f_2/a \leq x \leq s_2, \\
C_2F_2(x) + x - K & \text{if } s_1 < x \leq f_1/a, \\
\end{cases}

v_0(x, 2) = \begin{cases} g_2(x)B + h_1(x)C_1 + h_2(x) & \text{if } b_1 < x \leq f_2/a, \\
C_2F_2(x) & \text{if } b_2 < x \leq b_1, \\
C_2G_2(x) + x - K & \text{if } s_2 < x \leq s_1, \\
C_2G_2(x) + x - K & \text{if } s_1 < x \leq f_1/a, \\
C_1G_1(x) & \text{if } f_2/a \leq x \leq s_2, \\
C_2F_2(x) + x - K & \text{if } s_2 < x \leq f_1/a,
\end{cases}

v_1(x, 1) = \begin{cases} g_1(x)A + k_1(x)C_2 + k_2(x) & \text{if } s_2 < x \leq s_1, \\
C_2G_2(x) + x - K & \text{if } s_1 < x \leq f_1/a, \\
C_1G_1(x) & \text{if } f_2/a \leq x \leq s_2, \\
C_2F_2(x) + x - K & \text{if } s_2 < x \leq f_1/a,
\end{cases}

v_1(x, 2) = \begin{cases} g_1(x)A + k_1(x)C_2 + k_2(x) & \text{if } s_2 < x \leq s_1, \\
C_2G_2(x) + x - K & \text{if } s_1 < x \leq f_1/a, \\
C_1G_1(x) & \text{if } f_2/a \leq x \leq s_2, \\
C_2F_2(x) + x - K & \text{if } s_2 < x \leq f_1/a,
\end{cases}
\]

In Figure 3, these functions are so labelled in their corresponding intervals in Figure 2.
5. Variational inequalities and convexity. In this section, we consider the variational inequalities in (6) and related convexity inequalities.

5.1. Variational inequalities. Note that with the functions given in (15), all variational inequalities in (6) have to be satisfied, i.e., for \((x, \alpha) \in I_0 \times \mathcal{M}\),

\[
\begin{align*}
\rho v_0(x, \alpha) - \mathcal{A}v_0(x, \alpha) & \geq 0, \\
v_0(x, \alpha) - v_1(x, \alpha) + x + K & \geq 0,
\end{align*}
\]

(16)

In what follows, we consider these inequalities on each intervals: \([f_2/a, b_2], [b_2, b_1], [b_1, s_2], [s_2, s_1]\), and \([s_1, f_1/a]\).

First, we show that these inequalities on \([f_2/a, b_2]\) are automatically satisfied. Note that on \([f_2/a, b_2]\), we have

\[
\begin{align*}
v_0(x, 1) &= v_1(x, 1) - x - K, \\
v_0(x, 2) &= v_1(x, 2) - x - K,
\end{align*}
\]

(17)

\[
\begin{align*}
\rho v_0(x, 1) &= \mathcal{A}v_0(x, 1), \\
\rho v_0(x, 2) &= \mathcal{A}v_0(x, 2).
\end{align*}
\]

We need to show

\[
\begin{align*}
\rho v_0(x, 1) & \geq \mathcal{A}v_0(x, 1), \\
\rho v_0(x, 2) & \geq \mathcal{A}v_0(x, 2), \\
v_1(x, 1) & \geq v_0(x, 1) + x - K, \\
v_1(x, 2) & \geq v_0(x, 2) + x - K.
\end{align*}
\]

(18)

It is easy to see that the last two inequalities follow directly from the first two equalities in (17). To see the first inequality \(\rho v_0(x, 1) \geq \mathcal{A}v_0(x, 1)\), note that it can be written in terms of \(v_1(x, 1)\) and \(v_1(x, 2)\):

\[
\rho (v_1(x, 1) - x - K) \geq (f_1 - ax)(v'_1(x, 1) - 1) + \lambda_1(v_1(x, 2) - v_1(x, 1)),
\]

which is equivalent to

\[-\rho(x + K) \geq -(f_1 - ax), \text{ for } x < b_2,\]

because \(\rho v_1(x, 1) = \mathcal{A}v_1(x, 1)\). The above inequality is clearly satisfied because \(b_2 = (f_2 - \rho K)/(\rho + a)\) and \(f_2 < f_1\).

Similarly, on \([s_1, f_1/a]\), we can use \(s_1 = (f_1 + \rho K)/(\rho + a)\) and show that all VIs in (16) hold.
Next, we consider the VIs on $[b_2, b_1]$. We have

$$
\begin{align*}
  v_0(x, 1) &= v_1(x, 1) - x - K, \\
  \rho v_0(x, 2) &= A v_0(x, 2), \\
  \rho v_1(x, 1) &= A v_1(x, 1), \\
  \rho v_1(x, 2) &= A v_1(x, 2).
\end{align*}
$$

We need the following inequalities to hold:

$$
\begin{align*}
  \rho v_0(x, 1) &\geq A v_0(x, 1), \\
  v_0(x, 2) &\geq v_1(x, 2) - x - K, \\
  v_1(x, 1) &\geq v_0(x, 1) + x - K, \\
  v_1(x, 2) &\geq v_0(x, 2) + x - K.
\end{align*}
$$

The third inequality is automatically satisfied. The second and forth ones can be written as:

$$
-K \leq v_0(x, 2) - v_1(x, 2) + x \leq K.
$$

Finally, the first inequality in (20) can be given as

$$
v_0(x, 2) - v_1(x, 2) + x \leq \frac{1}{\lambda_1} [f_1 - \rho K - (\rho + a)x] - K.
$$

We can work out all needed inequalities this way on all other intervals and summarize these inequalities as follows:

$$
\begin{align*}
  &\text{On } [b_2, b_1]: \\
  &\text{On } [b_1, s_2]: \\
  &\text{On } [s_2, s_1]:
\end{align*}
$$

where $W_1(x) = v_0(x, 1) - v_1(x, 1) + x$ and $W_2(x) = v_0(x, 2) - v_1(x, 2) + x$.

5.2. **Convexity.** Recall that the value functions are convex on $\mathcal{I}_0$. We expect the solutions to the HJ equations in (6) to be also convex.

Recall also that

$$
G_i(x) = \frac{1}{\lambda_i} ((\rho + \lambda_i) F_i(x) + (a x - f_i) F_i'(x)),
$$

for $i = 1, 2$.

**Lemma 5.1.** $F_1, F_2, G_1, G_2$ are convex on $[f_2/a, f_1/a]$.

**Proof.** Clearly, both $F_1$ and $F_2$ are convex because their second derivatives are positive.

To show the convexities of $G_1$ and $G_2$, we first consider

$$
g(\xi) = (\gamma_1 + \gamma_2 - \gamma_3) u(\xi) - (1 - \xi) \frac{du}{d\xi}(\xi),
$$

with $u(\xi) = F(\gamma_1, \gamma_2; \gamma_3, \xi)$. Multiply its both sides by $-(1 - \xi)^{\gamma_1 + \gamma_2 - \gamma_3 - 1}$ to obtain

$$
-(1 - \xi)^{\gamma_1 + \gamma_2 - \gamma_3 - 1} g(\xi) = -(\gamma_1 + \gamma_2 - \gamma_3)(1 - \xi)^{\gamma_1 + \gamma_2 - \gamma_3 - 1} u(\xi) + (1 - \xi)^{\gamma_1 + \gamma_2 - \gamma_3} \frac{du}{d\xi}(\xi).
$$

The right hand side of the above equation is equal to

$$
d \frac{d}{d\xi} \left[ (1 - \xi)^{\gamma_1 + \gamma_2 - \gamma_3} F(\gamma_1, \gamma_2; \gamma_3, \xi) \right].
$$
We next apply the formula
\[
\frac{d^n}{d\xi^n} [(1 - \xi)^{\gamma_1 + \gamma_2 - \gamma_3} F(\gamma_1, \gamma_2; \gamma_3, \xi)]
= \frac{(\gamma_3 - \gamma_1)_{n}(\gamma_3 - \gamma_2)_{n}}{(\gamma_3)^n} (1 - \xi)^{\gamma_1 + \gamma_2 - \gamma_3 - n} F(\gamma_1, \gamma_2; \gamma_3 + n, \xi),
\]
with \( n = 1 \) and get
\[-(1 - \xi)^{\gamma_1 + \gamma_2 - \gamma_3 - 1} g(\xi) = \frac{(\gamma_3 - \gamma_1)(\gamma_3 - \gamma_2)}{\gamma_3} (1 - \xi)^{\gamma_1 + \gamma_2 - \gamma_3 - 1} F(\gamma_1, \gamma_2; \gamma_3 + 1, \xi).
\]
Hence we conclude that
\[ g(\xi) = \frac{(\gamma_3 - \gamma_1)(\gamma_3 - \gamma_2)}{\gamma_3} F(\gamma_1, \gamma_2; \gamma_3 + 1, \xi). \]
For \( u(\xi) = F \left( \frac{a}{a}, \frac{a + \lambda_1 + \lambda_2}{a}, \frac{a + \lambda_2}{a}, \xi \right) \), the corresponding \( g(\xi) \) is given by
\[ g(\xi) = \frac{\lambda_2 \lambda_1}{\rho + \lambda_2} F \left( \frac{\rho + \lambda_1 + \lambda_2}{a}, \frac{\rho + \lambda_2}{a}; \frac{\rho + \lambda_2}{a} + 1, \xi \right). \]
Then the convexity of \( F \left( \frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}, \frac{\rho + \lambda_2}{a} + 1, \xi \right) \) implies that \( g(\xi) \) is convex. It is easy to check with change of variable \( t = (ax - f_2)/(f_1 - f_2) \) that \( G_1(x) = (\lambda_1/a)g(\xi) \). So \( G_1 \) is convex. Similarly, we can show the convexity of \( G_2 \).

**Lemma 5.2.** \( h_1(x) \) and \( k_1(x) \) are convex.

**Proof.** Here, we only show the convexity of \( h_1(x) \). The convexity for \( k_1(x) \) can be given in a similar way. Recall that
\[ h_1(x) = \frac{\lambda_2}{\gamma_3} \frac{(ax - f_2)^{\frac{a + \lambda_2}{a}}}{(a - f_2) \int_{b_2}^{x} (as - f_2)^{\frac{a + \lambda_2}{a} - 1} F(1) ds}, \]
where
\[ F_1(x) = F \left( \gamma_1, \gamma_2; \gamma_3, \frac{ax - f_2}{f_1 - f_2} \right) \text{ with } \gamma_1 = \frac{\rho}{a}, \gamma_2 = \frac{\rho + \lambda_1 + \lambda_2}{a} \text{ and } \gamma_3 = \frac{\rho + \lambda_2}{a}. \]
Let
\[ w_1(\xi) = h_1(x) = h_1 \left( \frac{(f_1 - f_2)t + f_2}{a} \right), \text{ with } t = \frac{ax - f_2}{f_1 - f_2}. \]
It follows that
\[ w_1(\xi) = \frac{\lambda_2}{a} \xi^{\gamma_3} \int_{b_2}^{\xi} r^{\gamma_3 - 1} F(\gamma_1, \gamma_2; \gamma_3, r) dr, \]
where \( b_2 = (ab_2 - f_2)/(f_1 - f_2) \). Note that
\[ \int F(\alpha, \beta; \gamma, \xi) \xi^{\gamma - 1} dt = \frac{\xi^\gamma}{\gamma} F(\alpha, \beta; \gamma + 1, \xi) + k. \]
Apply the above formula, we obtain
\[ w_1(\xi) = \frac{\lambda_2}{a \gamma_3} \left[ F(\gamma_1, \gamma_2; \gamma_3 + 1, \xi) - F(\gamma_1, \gamma_2; \gamma_3 + 1, \xi) \right]. \]
Recall the derivative formula for hypergeometric function:
\[ \frac{d^m}{d\xi^m} F(\alpha, \beta; \gamma, \xi) = \frac{(\alpha)_m(\beta)_m}{(\gamma)_m} F(\alpha + m, \beta + m; \gamma + m, \xi). \]
It follows that
$$w''(\xi) = \frac{\lambda_2 \gamma_1 (\gamma_1 + 1) \gamma_2 (\gamma_2 + 1)}{a \gamma_3 (\gamma_3 + 1) (\gamma_3 + 2)} F(\gamma_1 + 2, \gamma_2 + 2; \gamma_3 + 3, \xi).$$

In view of this and the convexity of the hypergeometric functions with positive parameters, the convexity of $w_1(\xi)$ follows on $[0, 1]$. So is the convexity of $h_1(x)$. □

**Lemma 5.3.** $g_2 B + h_1 C_1 + h_2$ and $g_1 A + k_1 C_2 + k_2$ are convex provided that
$$C_1 \geq 0, \quad C_2 \geq 0, \quad A + A_0 \geq 0, \quad B + B_0 \geq 0,$$
(22)
where
$$A_0 = \frac{\lambda_1}{a} \left( \frac{f_1 - a s_1}{\rho + \lambda_1 + a} - \frac{f_1 - a K}{\rho + \lambda_1} \right) \quad \text{and} \quad B_0 = \frac{\lambda_2}{a} \left( \frac{ab_2 - f_2}{\rho + \lambda_2 + a} + \frac{f_2 + a K}{\rho + \lambda_2} \right).$$

**Proof.** It is easy to see that both $g_1(x)$ and $g_2(x)$ are convex. In addition, note that $g_1(A) + k_2$ can be written as $g_1(A + A_0) + f_1$ linear function. So $A + A_0 \geq 0$ implies that $g_1(A + k_2)$ is convex. Then in view of the convexity of $k_1(x)$ in Lemma 5.2, it follows that $g_1(A + k_1 C_2 + k_2$ is convex. Similarly, we can show the convexity of $g_2 B + h_1 C_1 + h_2$. □

To guarantee the convexity of the functions $v_i(x, \alpha)$, it is sufficient to require the convexity of $v_0(x, 1)$ at $x = b_1$ and $v_1(x, 2)$ at $x = s_2$.

The convexity of $v_0(x, 1)$ at $x = b_1$ is equivalent to
$$(v_0(b_1, 1))'_- \leq (v_0(b_1, 1))'_+.$$ Therefore, we need
$$C_1 F_1'(b_1) - 1 \leq C_2 G_2'(b_1).$$
(23)

Similarly, The convexity of $v_1(x, 2)$ at $x = s_2$ requires
$$C_2 G_1'(s_2) \leq C_2 F_2'(s_2) + 1.$$ (24)

**Theorem 5.1.** Assume that there exist $b_1$ and $s_2$ such that (a) the equalities in (14) hold with invertible matrices; (b) the additional VI inequalities in (21) hold; (c) the inequalities in (22) hold; (d) the convexity inequalities in (23) and (24) hold. Then, $v_i(x, \alpha)$ defined in (15) satisfy the HJ equations (6).

6. A verification theorem.

**Theorem 6.1.** Assume the conditions of Theorem 5.1. Then,
(a) $v(x, i) = V(x, i), \quad i = 1, 2$.
(b) Moreover, let
$$D_b = (b_1, f_1/a) \times \{1\} \cup (b_2, f_1/a) \times \{2\},$$
$$D_s = (f_2/a, s_1) \times \{1\} \cup (f_2/a, s_2) \times \{2\}$$
denote the continuation regions. The set of stopping times in $\Lambda_0$ and $\Lambda_1$ can be defined as the first exit times from these continuation regions in sequence. Let $\Lambda^*_0 = (\tau^*_1, \tau^*_2, \tau^*_3, \tau^*_4, \ldots)$, where $\tau^*_1 = \inf\{t \geq \tau^*_1 : (X_t, \alpha_t) \not\in D_1\}$, $\tau^*_2 = \inf\{t \geq \tau^*_2 : (X_t, \alpha_t) \not\in D_2\}$, $\tau^*_3 = \inf\{t \geq \tau^*_3 : (X_t, \alpha_t) \not\in D_3\}$, $\tau^*_4 = \inf\{t \geq \tau^*_4 : (X_t, \alpha_t) \not\in D_4\}$, and let $\Lambda^*_1 = (\tau^*_1, \tau^*_2, \tau^*_3, \ldots)$, where $\tau^*_1 = \inf\{t \geq \tau^*_1 : (X_t, \alpha_t) \not\in D_1\}$, $\tau^*_2 = \inf\{t \geq \tau^*_2 : (X_t, \alpha_t) \not\in D_2\}$, $\tau^*_3 = \inf\{t \geq \tau^*_3 : (X_t, \alpha_t) \not\in D_3\}$, $\ldots$. If $v_0(x) \geq 0$ and $\tau_n \to \infty$, a.s., then, $\Lambda_0^*$ and $\Lambda_1^*$ are optimal.
Proof. We only sketch the proof because it is similar to that of Zhang and Zhang [27, Theorem 5]. First, for any stopping times $0 \leq \theta_1 \leq \theta_2$, we can show as in [27] that

$$Ee^{-\rho \theta_1}v_i(X_{\theta_1}, \alpha_{\theta_1}) \geq Ee^{-\rho \theta_2}v_i(X_{\theta_2}, \alpha_{\theta_2}),$$

for $i = 0, 1$. For any given $\Lambda_0$, it follows from this inequality (with $\theta_1 = 0$ and $\theta_2 = \tau_i^0$) and the VIs in (6) that

$$v_0(x, \alpha) \geq E \left( e^{-\rho \tau_i^0}v_0(X_{\tau_i^0}, \alpha_{\tau_i^0}) \right) \geq E \left( e^{-\rho \tau_i^0}v_1(X_{\tau_i^0}, \alpha_{\tau_i^0}) - X_{\tau_i^0} - K \right) \geq E \left( e^{-\rho \tau_i^0}v_1(X_{\tau_i^0}, \alpha_{\tau_i^0}) - E \left( e^{-\rho \tau_i^0}v_1(X_{\tau_i^0}, \alpha_{\tau_i^0}) \right) \right) \geq E \left( e^{-\rho \tau_i^0}v_0(X_{\tau_i^0}, \alpha_{\tau_i^0}) + X_{\tau_i^0} - K \right) - E \left( e^{-\rho \tau_i^0}v_1(X_{\tau_i^0}, \alpha_{\tau_i^0}) + E \left( e^{-\rho \tau_i^0}v_1(X_{\tau_i^0}, \alpha_{\tau_i^0}) \right) \right).$$

(25)

Continue this way and recall $v_0 \geq 0$ to obtain

$$v_0(x, \alpha) \geq E \sum_{n=1}^{\infty} \left[ e^{-\rho \tau_n^0} (X_{\tau_n^0} - K) - e^{-\rho \tau_n^0} (X_{\tau_n^0} + K) \right].$$

It follows that $v_0(x, \alpha) \geq V_0(x, \alpha)$. Similarly, we can show $v_1(x, \alpha) \geq V_1(x, \alpha)$.

To establish the equalities with $\Lambda_i = \Lambda_i^*$, first note that, in view of Lemma 8.3 (Appendix), $\tau_{n^*}^b$ and $\tau_{n^*}^s$ are finite a.s. for each $n$. Using this condition, the inequalities in (25) become equalities when $\tau_i^0$ is replaced by $\tau_i^{n^*}$, and $\tau_i^b$ is replaced by $\tau_i^{n^*}$, respectively. Finally, the boundedness of $v_0$ and $\tau_{n^*} \to \infty$ imply, for $i = 0$,

$$v_0(x, \alpha) = E \sum_{n=1}^{\infty} \left[ e^{-\rho \tau_n^{n^*}} (X_{\tau_n^{n^*}} - K) - e^{-\rho \tau_n^{n^*}} (X_{\tau_n^{n^*}} + K) \right] = V_0(x, \alpha).$$

Similarly, we can show the case when $i = 1$. \qed

Remark 6.1. We point out that a sufficient condition for $\tau_{n^*} \to \infty$ can be given by $s_2 - b_1 > 2K$ following the proof in [27]. (This inequality is satisfied in all cases in our numerical example in the next section.)

7. A numerical example.

7.1. Model calibration and state estimation. First we give a model calibration method. Let $Z_k = X_{k\delta}$ with $\delta > 0$ being a discretization step size. Then, $Z_k$ can be approximated by the solution of the follow equation:

$$Z_{k+1} = (1 - a\delta)Z_k + ab\delta + \varepsilon_k,$$

(26)

where $\varepsilon_k = \int_{k\delta}^{(k+1)\delta} f(\alpha_t)dt$ represents system noise.

In view of this, $Z_{n\delta}$ is an autoregressive process of order 1. Following standard AR(1) estimation (least square) method, we can obtain the estimates for $a$, $b$, and its variance $\Sigma^2$. Plugging back these values to (26) to obtain the values for $\varepsilon_k$. An estimate for the state process $\alpha_t$ can be given in terms of $\varepsilon_k$: for $t \in (k\delta, (k + 1)\delta]$,

$$\hat{\alpha}_t = \begin{cases} 1 & \text{if } \varepsilon_k \geq 0, \\ 2 & \text{if } \varepsilon_k < 0. \end{cases}$$

To estimate $f_1$, $f_2$, $\lambda_1$, and $\lambda_2$, let $f_1 = \mu + \sigma_1$ and $f_2 = \mu - \sigma_2$, for some $\mu$, $\sigma_1$, and $\sigma_2$, with $\nu_1\sigma_1 - \nu_2\sigma_2 = 0$, where $(\nu_1, \nu_2) = (\lambda_2/(\lambda_1 + \lambda_2), \lambda_1/(\lambda_1 + \lambda_2))$. 

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Let $\bar{\varepsilon} = \left( \sum_{k=0}^{n-1} \varepsilon_k \right) / n$. Then, $\mu \approx \bar{\varepsilon} / \delta$. In addition, using Yin an Zhang [26, Theorem 5.9], we can show

$$E(\varepsilon_k - \bar{\varepsilon})^2 \approx \delta \left( \frac{2\lambda_1 \lambda_2 (\sigma_1 + \sigma_2)^2}{(\lambda_1 + \lambda_2)^3} \right).$$

Let

$$\sigma_0^2 = \frac{\sum_{k=0}^{n-1} (\varepsilon_k - \bar{\varepsilon})^2}{n - 1}.$$

Then, by the Law of Large Numbers, we have

$$\sigma_0^2 \approx \delta \left( \frac{2\lambda_1 \lambda_2 (\sigma_1 + \sigma_2)^2}{(\lambda_1 + \lambda_2)^3} \right).$$

Using $\nu_1 \sigma_1 = \nu_2 \sigma_2$, we have

$$\sigma_1 = \frac{\sigma_0}{\sqrt{\delta}} \sqrt{\frac{\lambda_1 (\lambda_1 + \lambda_2)}{2\lambda_2}} \text{ and } \sigma_2 = \frac{\sigma_0}{\sqrt{\delta}} \sqrt{\frac{\lambda_2 (\lambda_1 + \lambda_2)}{2\lambda_1}},$$

Finally, we estimate $\lambda_1$ and $\lambda_2$. Let $R = \nu_1 / \nu_2$. Then, $\lambda_2 = R \lambda_1$.

$$R_1 = \#\{ k : \varepsilon_k < 0 \text{ and } \varepsilon_{k+1} \geq 0 \},$$
$$R_2 = \#\{ k : \varepsilon_k > 0 \text{ and } \varepsilon_{k+1} \leq 0 \}.$$

Then, it follows that

$$\frac{R_1}{\lambda_1} + \frac{R_2}{\lambda_2} = T.$$

Therefore, the jump rates are given by

$$\left\{ \begin{array}{l}
\lambda_1 = \frac{1}{T} \left( \frac{R_1 + R_2}{R} \right), \\
\lambda_2 = \frac{1}{T} (RR_1 + R_2).
\end{array} \right.$$

7.2. Backtesting with DJIA 1961-1980. We use Dow Jones Industrial Average daily closing prices from 1961 to 1980 to backtest our trading rules. In particular, let $c_0, c_1, c_2, \ldots$ denote the daily closing prices of the index. We take $S_{k\delta} = \log(c_k)$ with $\delta = 1/252$ and use the daily prices from the beginning of 1961 to the end of 1970 to calibrate the model. We obtain

$$a = 0.1528, \ b = 6.4813, \ f_1 = 1.09, \ f_2 = -1.20, \ \lambda_1 = 104.35, \ \lambda_2 = 114.88.$$

Then, we take $X_{k\delta} = S_{k\delta} - h$, $\rho = 1$, and $K = 0.01$ and obtain the corresponding buy and sell thresholds for trading in 1971:

$$b_2 = -1.049618, \ b_1 = -0.027672, \ s_2 = 0.032443, \ s_1 = 0.954198.$$

At the end of 1971, we update the system parameter values using the most recent data (1971) and dropping the 1961 prices. We keep rolling forward this way. The parameter values are given in Table 1 and the corresponding threshold levels are provided in Table 2. In addition, the conditions required in Theorem 5.1 are satisfied in all these cases.
In each trading year, a buying signal is triggered when \((X_t, \hat{\alpha}_t)\) exits \(D_b\) and a selling signal is generated when \((X_t, \hat{\alpha}_t)\) exits \(D_s\). In Figure 4, we define \(b[n]\) as a piecewise constant function determined by the \(b\)-column in Table 1. For example, 

\[ b[n] = 6.4813 \]

for \(n = 0, 1, \ldots, 252\) corresponding to the prices in 1971. Likewise, we define \(s_1[n]\), \(s_2[n]\), \(b_1[n]\), and \(b_2[n]\) piecewisely using the corresponding columns in Table 2. Also, in Figure 4, \(X_{n\delta} = \log(c[n]) - b[n]\) is plotted.

Initially, we allocate the capital of $100K. When a trading signal is triggered, buy (and sell) the index with the entire account balance less the transaction fees.
The corresponding equity curve is also provided in Figure 4. There are five trades between 1971-1980. The ending balance is $142,818.61 which amounts 42.28% gain.

8. **Conclusion.** This paper considers a mean-reversion trading rule under a Markov chain model. It is shown that the optimal trading rule can be given in terms of four threshold levels that can be obtained by solving algebraic like equations. Such feature is attractive from practical viewpoints because they are easy to implement.

It would be interesting to study related problems with regime switching. For example, the rate of mean reversion and equilibrium levels are regime dependent.

In this connection, one may introduce a two-time-scale Markov chain so that the ‘fast’ states correspond to short term events and the ‘slow’ states correspond to market trends. In addition, related state estimation may arise due to incomplete observation of the ‘slow’ components.

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**Appendix.** In this section, we provide three technical lemmas used in this paper.

**Lemma 8.1.** Under Assumption (A3), we have

\[
\begin{align*}
\lim_{\xi \to 1^-} F \left( \frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_2}{a}, \xi \right) &= \infty, \\
\lim_{\xi \to 0^+} F \left( \frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_2 + a}{a}, 1 - \xi \right) &= \infty, \\
\lim_{\xi \to 1^-} F \left( \frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_1}{a}, \xi \right) &= \infty, \\
\lim_{\xi \to 0^+} F \left( \frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_1 + a}{a}, 1 - \xi \right) &= \infty.
\end{align*}
\]

**Proof.** First, note that the value of \( F(\gamma_1, \gamma_2; \gamma_3, 1) \) can be given in terms of the sum of the hypergeometric series

\[
\sum_{n=0}^{\infty} c_n = \sum_{n=0}^{\infty} \frac{(\gamma_1)_n (\gamma_2)_n}{n!(\gamma_3)_n}.
\]

The ratio of the consecutive terms in the hypergeometric series is given by

\[
\frac{c_{n-1}}{c_n} = \frac{n(n-1+\gamma_3)}{(n-1+\gamma_1)(n-1+\gamma_2)} = 1 + \frac{\gamma_3 - \gamma_1 - \gamma_2 + 1}{n} + O(n^{-2}).
\]

Then, it follows from Bromwich [4, §79, p. 240] that the series \( \sum c_n \) is absolutely convergent if \( \text{Re}(\gamma_3 - \gamma_1 - \gamma_2) > 0 \) and it is divergent (unless being a finite sum) if \( \text{Re}(\gamma_3 - \gamma_1 - \gamma_2) \leq 0 \).

For the function \( F \left( \frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_2}{a}, \xi \right) \), clearly, the corresponding \( \gamma_3 - \gamma_1 - \gamma_2 = -(\rho + \lambda_1)/a < 0 \). This implies that \( \lim_{\xi \to 1^-} F \left( \frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_2}{a}, \xi \right) = \infty \).

Also, for the function \( F \left( \frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_1 + a}{a}, 1 - \xi \right) \), the corresponding \( \gamma_3 - \gamma_1 - \gamma_2 = 1 - (\rho + \lambda_2)/a < 0 \) by (A3). Therefore, we have

\[
\lim_{\xi \to 1^-} F \left( \frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}; \frac{\rho + \lambda_2 + a}{a}, \xi \right) = \infty.
\]
Hence,
\[
\lim_{\xi \to 0^+} F \left( \frac{\rho}{a}, \frac{\rho + \lambda_1 + \lambda_2}{a}, \frac{\rho + \lambda_2 + a}{a}, 1 - \xi \right) = \infty.
\]
Similarly, we can show the divergence of the other two functions. \(\square\)

**Lemma 8.2.** The following hold:

(a) \(b_2 = f_2 - \rho K\) and \(s_1 = f_1 + \rho K\).

(b) \(v_0(x, 2)\) is differentiable at \(x = b_2\) and \(v_1(x, 1)\) is differentiable at \(x = s_1\).

Hence, each \(v_i(x, \alpha), i = 0, 1\) and \(\alpha = 1, 2\), is differentiable at these two points.

**Proof.** First, we show \(b_2 = (f_2 - \rho K)/(\rho + a)\). Note that, for \(b_2 \leq x \leq b_1\), \(\rho v_0(x, 2) = A v_0(x, 2)\). It follows that
\[
(v_0(b_2, 2))'_+ = \frac{(\rho + \lambda_2)v_0(b_2, 2) - \lambda_2 v_0(b_2, 1)}{f_2 - ab_2}.
\]
Note also that, for \(x\) near \(b_2\), \(\rho v_1(x, 2) = A v_1(x, 2)\). Therefore, we have
\[
(v_1(b_2, 2))' = \frac{(\rho + \lambda_2)v_1(b_2, 2) - \lambda_2 v_1(b_2, 1)}{f_2 - ab_2}.
\]
Recall that \(v_0(x, 1) = v_1(x, 1) - x - K\) for \(x\) near \(b_2\) and \(v_0(x, 2) = v_1(x, 2) - x - K\) for \(x \leq b_2\). The convexity at \(x = b_2\) implies that \((v_0(b_2, 2))'_- \leq (v_0(b_2, 2))'_+\). Therefore,
\[
\frac{(\rho + \lambda_2)v_1(b_2, 2) - \lambda_2 v_1(b_2, 1)}{f_2 - ab_2} - 1 \leq \frac{(\rho + \lambda_2)v_0(b_2, 2) - \lambda_2 v_0(b_2, 1)}{f_2 - ab_2}.
\]
Using \(v_0(b_2, 1) = v_1(b_1, 1) - b_2 - K\) and \(v_0(b_2, 2) = v_1(b_2, 2) - b_2 - K\) and the fact that \(f_2 - ab_2 < 0\), we can show
\[
b_2 \geq \frac{f_2 - \rho K}{\rho + a}.
\]
To establish the opposite inequality, note that, for \(x < b_2\), \(\rho v_0(x, 2) \geq A v_0(x, 2)\), \(v_0(x, 1) = v_1(x, 1) - x - K\), and \(v_0(x, 2) = v_1(x, 2) - x - K\). It follows that
\[
\rho(v_1(x, 2) - x - K) \geq (f_2 - ax)(v_1(x, 2) - 1) + \lambda_2(v_0(x, 1) - v_0(x, 2))
\]
\[
= (f_2 - ax)(v_1(x, 2) - 1) + \lambda_2(v_1(x, 1) - v_1(x, 2)).
\]
Recall that \(\rho v_1(x, 2) = A v_1(x, 2)\). We have
\[-\rho(x + K) \geq -(f_2 - ax), \text{ for } x < b_2.
\]
This leads to
\[
b_2 \leq \frac{f_2 - \rho K}{\rho + a}
\]
Therefore, the equality holds. This in turn implies the equality in (27) holds. So is the differentiability of \(v_0(x, 2)\) at \(x = b_2\).

Similarly, we can show \(s_1 = (f_1 + \rho K)/(\rho + a)\) and \(v_1(x, 1)\) is differentiable at \(x = s_1\). \(\square\)

**Lemma 8.3.** For any given \(z_1, z_2 \in \mathcal{I}_0\), let \(\theta_1 = \inf\{t : X_t \geq z_1\}\) and \(\theta_2 = \inf\{t : X_t \leq z_2\}\). Then, under Assumption (A3), \(P(\theta_1 < \infty) = P(\theta_2 < \infty) = 1\).

**Proof.** Let \((z_0, z_1) \subset \mathcal{I}_0\) and \(\theta_0 = \inf\{t : X_t \notin (z_0, z_1)\}\). Let \(p(x, \alpha) = P(X_{\theta_0} = z_1 | X_0 = x, \alpha_0 = \alpha)\), for \(x \in (z_0, z_1)\) and \(\alpha \in \mathcal{M}\). Then,
\[
Ap(x, \cdot)(\alpha) = 0, \ p(z_0, \alpha) = 0, \ p(z_1, \alpha) = 1,
\]
for $\alpha = 1, 2$. Using the first equation in $A P(x, \cdot)(\alpha) = 0$, we have

$$p(x, 2) = p(x, 1) + \left(\frac{ax - f_1}{\lambda_1}\right) p'(x, 1),$$

and

$$p'(x, 2) = \left(\frac{\lambda_1 + a}{\lambda_1}\right) p'(x, 1) + \left(\frac{ax - f_1}{\lambda_1}\right) p''(x, 1).$$

Substitute these into the second equation in $A P(x, \cdot)(\alpha) = 0$ and simplify to obtain

$$(ax - f_1)(ax - f_2)p''(x, 1) + [(\lambda_1 + a)(ax - f_2) + \lambda_2(ax - f_1)]p'(x, 1) = 0.$$ 

Solve this equation with the boundary conditions $p(x, z_0) = 0$ and $p(x, z_1) = 1$ to obtain

$$p(x, 1) = \frac{\int_{z_0}^x (f_1 - ar)^{-\frac{\lambda_1 + a}{a}} (ar - f_2)^{-\frac{\lambda_2}{a}} dr}{\int_{z_0}^x (f_1 - ar)^{-\frac{\lambda_1 + a}{a}} (ar - f_2)^{-\frac{\lambda_2}{a}} dr}.$$ 

Similarly, we have

$$p(x, 2) = \frac{\int_{z_0}^x (f_1 - ar)^{-\frac{\lambda_1 + a}{a}} (ar - f_2)^{-\frac{\lambda_2 + a}{a}} dr}{\int_{z_0}^x (f_1 - ar)^{-\frac{\lambda_1 + a}{a}} (ar - f_2)^{-\frac{\lambda_2 + a}{a}} dr}.$$ 

Under Assumption (A3), it is easy to see, for any $\delta > 0$, that both integrals

$$\int_{z_0}^x (f_1 - ar)^{-\frac{\lambda_1 + a}{a}} (ar - f_2)^{-\frac{\lambda_2}{a}} dr$$

and

$$\int_{z_0}^{z_0 + \delta} (f_1 - ar)^{-\frac{\lambda_1 + a}{a}} (ar - f_2)^{-\frac{\lambda_2 + a}{a}} dr$$

tend to $\infty$, as $z_0 \to f_2/a$. It follows that

$$p(x, 1) \to 1 \text{ and } p(x, 2) \to 1, \text{ as } z_0 \to f_2/a.$$ 

Therefore, we have

$$P(\theta_1 < \infty) \geq p(x, 1)P(\alpha_0 = 1) + p(x, 2)P(\alpha_0 = 2) \to 1.$$ 

Hence, $P(\theta_1 < \infty) = 1$.

Similarly, we can consider the equations $A P(x, \cdot)(\alpha) = 0$ on interval $(z_2, z_0) \subset I_0$

with boundary conditions $p(z_0, \alpha) = 0$ and $p(z_2, \alpha) = 1$ and show that

$$p(x, 1) \to 1 \text{ and } p(x, 2) \to 1, \text{ as } z_0 \to f_1/a.$$ 

These lead to $P(\theta_2 < \infty) = 1$. 

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E-mail address: jtie@uga.edu

E-mail address: qzh@uga.edu