Optimal Real-Time Detection of a Drifting Brownian Coordinate

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Consider the motion of a Brownian particle in three dimensions, whose two spatial coordinates are standard Brownian motions with zero drift, and the remaining (unknown) spatial coordinate is a standard Brownian motion with a (known) non-zero drift. Given that the position of the Brownian particle is being observed in real time, the problem is to detect as soon as possible and with minimal probabilities of the wrong terminal decisions, which spatial coordinate has the non-zero drift. We solve this problem in the Bayesian formulation, under any prior probabilities of the non-zero drift being in any of the three spatial coordinates, when the passage of time is penalised linearly. Finding the exact solution to the problem in three dimensions, including a rigorous treatment of its non-monotone optimal stopping boundaries, is the main contribution of the present paper. To our knowledge this is the first time that such a problem has been solved in the literature.

1. Introduction

Imagine the motion of a Brownian particle in three dimensions, whose two spatial coordinates are standard Brownian motions with zero drift, and the remaining (unknown) spatial coordinate is a standard Brownian motion with a (known) non-zero drift. Given that the position $X$ of the Brownian particle is being observed in real time, the problem is to detect as soon as possible and with minimal probabilities of the wrong terminal decisions, which spatial coordinate has the non-zero drift. The purpose of the present paper is to derive the solution to this problem in the Bayesian formulation, under any prior probabilities of the non-zero drift being in any of the three spatial coordinates, when the passage of time is penalised linearly.

The loss to be minimised over sequential decision rules is expressed as the linear combination of the expected running time and the probabilities of the wrong terminal decisions. This problem formulation of sequential testing dates back to [25] and has been extensively studied to date (see [10] and the references therein). The linear combination represents the Lagrangian and once the optimisation problem has been solved in this form it will also lead to the solution of the constrained problem where upper bounds are imposed on the probabilities of the wrong terminal decisions. The central focus of the present paper is on the Lagrangian and the methods

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needed to solve the problem in this form. The constrained problem itself will not be considered in the present paper as this extension is somewhat lengthy and more routine.

Standard arguments show that the initial optimisation problem can be reduced to an optimal stopping problem for the posterior probability process \( \Pi \) of the non-zero drift being in the spatial coordinates given \( X \). A canonical example of \( X \) in one dimension is Brownian motion having one among two constant drifts (see [13] and [21]). In this case \( \Pi \) is a one-dimensional Markov/diffusion process. This problem has also been solved in finite horizon (see [7]). Books [22, Section 4.2] and [17, Section 21] contain expositions of these results and provide further details and references. Signal-to-noise ratio in these problems (defined as the difference between the two drifts divided by the diffusion coefficient) is constant. Sequential testing problems for \( X \) in one dimension where the signal-to-noise ratio is not constant were studied more recently in [8] and [10]. In these problems \( \Pi \) is no longer Markovian, however, the process \( (\Pi, X) \) is a two-dimensional Markov/diffusion process with the infinitesimal generator of parabolic type.

Another canonical example of \( X \) in one dimension is Brownian motion having one among three or more constant drifts (see [23] for a discrete time analogue). This problem has been studied more recently in [24] (see also [3] for a Poisson process analogue). The Markov/diffusion process \( \Pi \) is two-dimensional and its infinitesimal generator is also of parabolic type.

Related sequential testing problems for \( X \) in three or more dimensions when each coordinate process of \( X \) can have a non-zero drift have been studied in [12] and [1]. These problems contain an element of optimal control as well in deciding which coordinate process should be observed at any given time. The former paper contains a review of other related papers (such as [18]) and the latter paper shows that the Markov/diffusion process \( \Pi \) is one-dimensional even if one admits infinitely many coordinate processes of \( X \) in the problem formulation.

In contrast to all the sequential testing problems studied to date we will see below that the two-dimensional Markov/diffusion process \( \Pi \) in the sequential testing problem of the present paper has the infinitesimal generator of elliptic type. Moreover, we will also see that the optimal stopping boundaries are non-monotone as functions of the coordinate variables. This fact itself presents a formidable challenge as to our knowledge no rigorous treatment of non-monotone optimal stopping boundaries (curves) has been exposed in the probabilistic literature as yet. Finding the exact solution to the problem for \( X \) in three dimensions, including a rigorous treatment of its non-monotone optimal stopping boundaries, is the main contribution of the present paper. To our knowledge this is the first time that such a problem has been solved in the literature. The analogous problem for \( X \) in four/more dimensions introduces additional challenges for a rigorous treatment of ‘non-monotone’ optimal stopping boundaries (surfaces) and this is left for future research.

2. Outline of the paper

The exposition of the material is organised as follows. In Section 3 we derive the optimal stopping problem for \( \Pi = (\Pi_0, \Pi_1, \Pi_2) \) where \( \Pi^i \) is the posterior probability process of the non-zero drift being in the spatial coordinate \( i \) given \( X \) for \( i = 0, 1, 2 \). Due to \( \sum_{i=0}^{2} \Pi^i = 1 \) clearly only two coordinates of \( \Pi \) matter and this is utilised by passing to the posterior probability ratio process process \( \Phi = (\Phi^1, \Phi^2) \) defined by \( \Phi^i = \Pi^i/\Pi^0 \) for \( i = 1, 2 \). The processes \( \Pi \) and \( \Phi \) stand in one-to-one correspondence and we study the optimal stopping problem in terms of \( \Phi \) throughout. The previous considerations take place under the probability measure
\[ P_\pi = \sum_{i=0}^{2} \pi_i P_i \] where \( \pi_i \) is the prior probability of the non-zero drift being in the spatial coordinate \( i \) for \( i = 0, 1, 2 \). In Section 4 we show that a measure change from \( P_\pi \) to \( P_0 \) simplifies the setting upon verifying that the posterior probability ratio process \( \Phi^i \) coincides (up to the initial point) with the likelihood ratio process \( L^i \) of \( P_i \) and \( P_0 \) given \( X \) for \( i = 1, 2 \). This provides an explicit link between the process \( \Phi \) and the observed process \( X \).

In Section 5 we show that the process \( \Phi \) solves a coupled system of linear stochastic differential equations (of the geometric Brownian motion type) driven by two independent Brownian motions. This enables us to conclude that \( \Phi \) is a Markov/diffusion process and derive a closed form expression for its infinitesimal generator which is a second-order partial differential equation of elliptic type. The optimal stopping problem for \( \Phi \) is Bolza formulated and in Section 6 we disclose its Lagrange and Mayer formulations (see [17, Section 6] for the terminology). The Lagrange formulation is expressed in terms of the local time of \( \Phi \) on three straight lines which makes the optimal stopping problem more intuitive.

The observed process \( X \) is three-dimensional and in Section 7 we consider the same optimal stopping problem when \( X \) is two-dimensional. In this case \( \Phi \) is a one-dimensional Markov/diffusion process so that standard arguments enable us to solve the optimal stopping problem in a closed form. The reduction of dimension three to dimension two corresponds to either \( \Phi^1 \) or \( \Phi^2 \) becoming 0 which is a natural boundary point for both processes (cf. [6]). The one-dimensional results of Section 7 are used in Section 8 to derive existence of the optimal stopping set and derive basic properties of the value function. We show that the optimal stopping set consists of three convex sets separated by the three straight lines that support the local time of \( \Phi \) in the Lagrange formulation of the optimal stopping problem. Using symmetry arguments combined with the one-dimensional results of Section 7 we also derive the asymptotic behaviour of the optimal stopping boundaries at zero and infinity.

In Section 9 we derive a directional smooth fit between the value function and the loss function at the optimal stopping boundary. The proof of the smooth fit makes use of the asymptotic behaviour of the optimal stopping boundary at infinity to counter-balance the lack of the global smoothness of the underlying loss function in the optimal stopping problem. In Section 10 we show that the optimal stopping boundaries are non-monotone in either direction of the state space of \( \Phi \) and prove the existence of a ‘belly’ which determines their curvature/shape. These arguments rely on the general hint from [16, Remark 13] on establishing the absence of jumps of the optimal stopping boundaries and make use of Hopf’s boundary point lemma to derive a contradiction with the directional smooth fit.

In Section 11 we disclose the free-boundary problem which stands in one-to-one correspondence with the optimal stopping problem and establish the fact that the value function and the optimal stopping boundaries solve the free-boundary problem uniquely. In Section 12 we show that the optimal stopping boundaries can be characterised as the unique solution to a coupled system of nonlinear Fredholm integral equations. These equations can be used to find the optimal stopping boundaries numerically (using Picard iteration).

3. Formulation of the problem

In this section we formulate the sequential testing problem under consideration. The initial formulation of the problem will be revaluated under a change of measure in the next section.
1. We consider a Bayesian formulation of the problem where it is assumed that one observes a sample path of the three-dimensional Brownian motion \( X = (X_0, X_1, X_2) \), whose two coordinates \( X^0 \) and \( X^k \) are standard Brownian motions with zero drift, and the remaining (unknown) coordinate \( X^i \) is a standard Brownian motion having a (known) non-zero drift \( \mu \) with a probability \( \pi_i \in [0,1] \) for \( i = 0, 1, 2 \) where \( \pi_0 + \pi_1 + \pi_2 = 1 \) and \( i \neq j \neq k \) belong to \( \{0, 1, 2\} \). The problem is to detect which coordinate is drifting as soon as possible and with minimal probabilities of the wrong terminal decisions. This real-time detection problem belongs to the class of sequential testing problems as discussed in Section 1 above.

2. Standard arguments imply that the previous setting can be realised on a probability space \( (\Omega, \mathcal{F}, P_\pi) \) with the probability measure \( P_\pi \) decomposed as follows

\[
P_\pi = \pi_0 P_0 + \pi_1 P_1 + \pi_2 P_2
\]

for \( \pi = (\pi_0, \pi_1, \pi_2) \in [0,1]^3 \) satisfying \( \pi_0 + \pi_1 + \pi_2 = 1 \) where \( P_\pi \) is the probability measure under which the observed process \( X \) has the \( i \)-th coordinate equal to a standard Brownian motion with drift \( \mu \), and the remaining two coordinates are standard Brownian motions with zero drift for \( i = 0, 1, 2 \), with the three coordinates being independent. This can be formally achieved by introducing an unobservable random variable \( \theta \) taking values 0, 1, 2 with probabilities \( \pi_0, \pi_1, \pi_2 \) in [0,1] satisfying \( \pi_0 + \pi_1 + \pi_2 = 1 \) and being independent from three (mutually independent) standard Brownian motions \( B^0, B^1, B^2 \) so that \( X = (X^0, X^1, X^2) \) after starting at a point in \( \mathbb{R}^3 \) solves the system of stochastic differential equations

\[
dX^i_t = \mu I(\theta = i) \, dt + dB^i_t
\]

for \( i = 0, 1, 2 \). Due to stationary and independent increments of Brownian motion it is clear that the starting point of \( X \) plays no role in the sequel so we will leave it unspecified.

3. Being based upon the continued observation of \( X \), the problem is to test sequentially the hypotheses \( H_0 : \theta = 0 \), \( H_1 : \theta = 1 \), \( H_2 : \theta = 2 \) with a minimal loss. For this, we are given a sequential decision rule \( (\tau, d_\tau) \), where \( \tau \) is a stopping time of \( X \) (i.e. a stopping time with respect to the natural filtration \( \mathcal{F}^X = \sigma(X_s | 0 \leq s \leq t) \) of \( X \) for \( t \geq 0 \)), and \( d_\tau \) is an \( \mathcal{F}^X_\tau \)-measurable random variable taking values in the set \( \{0, 1, 2\} \). After stopping the observation of \( X \) at time \( \tau \), the terminal decision function \( d_\tau \) takes value \( i \) if and only if the hypothesis \( H_i \) is to be accepted for \( i = 0, 1, 2 \). With a constant \( c > 0 \) given and fixed, the problem then becomes to compute the risk function

\[
V(\pi) = \inf_{(\tau, d_\tau)} \mathbb{E}_\pi \left[ \tau + c \left( I(\theta = 0, d_\tau \neq 0) + I(\theta = 1, d_\tau \neq 1) + I(\theta = 2, d_\tau \neq 2) \right) \right]
\]

for \( \pi = (\pi_0, \pi_1, \pi_2) \in [0,1]^3 \) with \( \pi_0 + \pi_1 + \pi_2 = 1 \) and find the optimal decision rule \( (\tau_*, d^*_\tau) \) at which the infimum in (3.3) is attained. Note that \( \mathbb{E}_\pi(\tau) \) in (3.3) is the expected waiting time until the terminal decision is made, and \( P_\pi(\theta = i, d_\tau \neq i) \) are probabilities of the wrong terminal decisions for \( i = 0, 1, 2 \). Clearly, each probability \( P_\pi(\theta = i, d_\tau \neq i) \) could be further decomposed into the sum of two probabilities \( P_\pi(\theta = i, d_\tau = j) \) and \( P_\pi(\theta = i, d_\tau = k) \) for \( i = 0, 1, 2 \) and \( i \neq j \neq k \) in \( \{0, 1, 2\} \), and each of the six resulting probabilities could have a different constant/weight placed in front of them, however, since the constrained problems are not considered in the present paper as explained in the introduction, we only focus on the canonical setting of a single constant/weight \( c \) given in (3.3) above.
4. To tackle the sequential testing problem (3.3) we consider the posterior probability process
\[ \Pi^i_t = P_\pi(\theta = i \mid \mathcal{F}_t^X) \]
for \( i = 0, 1, 2 \) and \( t \geq 0 \). Noting that for any decision rule \((\tau, d_\tau)\) we have
\[ \sum_{i=0}^{2} P_\pi(\theta = i, d_\tau \neq i) = \sum_{i=0}^{2} E_\pi[(1 - \Pi^i_\tau)I(d_\tau = i)] \]
where in the final equality we use that \( \Pi^0_\tau + \Pi^1_\tau + \Pi^2_\tau = 1 \), it follows that
\[ \sum_{i=0}^{2} P_\pi(\theta = i, d_\tau \neq i) = \sum_{i=0}^{2} E_\pi[(1 - \Pi^i_\tau)I(d_\tau = i)] \]
where equality is attained at the decision rule \((\tau, \hat{d}_\tau)\) with \( \hat{d}_\tau \) defined as follows
\[ \hat{d}_\tau = 0 \text{ if } (1 - \Pi^0_\tau) \leq (1 - \Pi^1_\tau) \land (1 - \Pi^2_\tau) \]
\[ = 1 \text{ if } (1 - \Pi^1_\tau) \leq (1 - \Pi^0_\tau) \land (1 - \Pi^2_\tau) \]
\[ = 2 \text{ if } (1 - \Pi^2_\tau) \leq (1 - \Pi^0_\tau) \land (1 - \Pi^1_\tau). \]
This shows that the problem (3.3) is equivalent to the optimal stopping problem
\[ V(\pi) = \inf_{\tau} E_\pi[\tau + M(\Pi_\tau)] \]
where the infimum is taken over all stopping times \( \tau \) of \( X \), and the function \( M \) is given by
\[ M(\pi) = c((1 - \pi_0) \land (1 - \pi_1) \land (1 - \pi_2)) \]
for \( \pi = (\pi_0, \pi_1, \pi_2) \in [0, 1]^3 \) with \( \pi_0 + \pi_1 + \pi_2 = 1 \). For this reason we focus on solving the optimal stopping problem (3.8) in what follows.

4. Measure change

In this section we show that changing the probability measure \( P_\pi \) for \( \pi \in [0, 1]^3 \) with \( \pi_0 + \pi_1 + \pi_2 = 1 \) to \( P_0 \) provides important simplifications of the setting which make the subsequent analysis more transparent. The change of measure argument is presented in Lemma 1 below. This is then followed by a reformulation of the optimal stopping problem (3.8) under the new probability measure \( P_0 \) in Proposition 2 below.

1. To connect the process \( \Pi^i \) in (3.8) to the observed process \( X \) we consider the likelihood ratio process \( L = ((L^1_t, L^2_t))_{t \geq 0} \) defined by
\[ L^i_t = \frac{dP_{i,t}}{dP_{0,t}} \]
where \( P_{i,t} \) and \( P_{0,t} \) denote the restrictions of \( P_i \) and \( P_0 \) to \( \mathcal{F}_t^X \) for \( t \geq 0 \) and \( i = 1, 2 \). Using
that \(((X_t^0 - \mu t, X_t^1))_{t \geq 0}\) and \(((X_t^0, X_t^1 - \mu t))_{t \geq 0}\) define standard two-dimensional Brownian motions under \(P_0\) and \(P_t\) respectively, by the Cameron-Martin-Girsanov theorem (see e.g. [11, Theorem 5.1, p. 191]) one finds that

\[
L_i^t = e^{\mu (X_i^t - X_i^0)}
\]

for \(t \geq 0\) and \(i = 1, 2\). A direct calculation indicated below shows that the posterior probability ratio process \(\Phi = ((\Phi_i^1, \Phi_i^2))_{t \geq 0}\) defined by

\[
\Phi_i^j = \frac{\Pi_i^j}{\Pi_0^j}
\]

can be expressed in terms of \(L\) (and hence \(X\) as well) as follows

\[
\Phi_i^j = \Phi_0^j L_i^t
\]

for \(t \geq 0\) where \(\Phi_0^i = \pi_i / \pi_0\) for \(i = 1, 2\). Recalling that \(\Pi_0^1 + \Pi_1^1 + \Pi_2^1 = 1\) and formally setting \(\Phi_0^i \equiv 1\) it is easily seen that (4.3) is equivalent to

\[
\Pi_i^1 = \frac{\Phi_i^1}{1 + \Phi_i^1 + \Phi_2^2}
\]

for \(t \geq 0\) and \(i = 0, 1, 2\).

2. To derive (4.3)-(4.5) one may use a standard rule for the Radon-Nikodym derivatives based on (3.1) that gives

\[
\Pi_0^1 = P_\pi(\theta = 0 | F_t^X) = \sum_{i=0}^{2} \pi_i P_i(\theta = 0 | F_t^X) \frac{dP_{i,t}}{dP_{\pi,t}} = \pi_0 \frac{dP_{0,t}}{dP_{\pi,t}} = \frac{1}{1 + \pi_1 \frac{dP_{1,t}}{dP_{\pi,t}} + \pi_2 \frac{dP_{2,t}}{dP_{\pi,t}}}
\]

\[
\Pi_1^1 = P_\pi(\theta = 1 | F_t^X) = \sum_{i=0}^{2} \pi_i P_i(\theta = 1 | F_t^X) \frac{dP_{i,t}}{dP_{\pi,t}} = \pi_1 \frac{dP_{1,t}}{dP_{\pi,t}} = \frac{\pi_1 \frac{dP_{1,t}}{dP_{\pi,t}}}{1 + \pi_1 \frac{dP_{1,t}}{dP_{\pi,t}} + \pi_2 \frac{dP_{2,t}}{dP_{\pi,t}}}
\]

\[
\Pi_2^1 = P_\pi(\theta = 2 | F_t^X) = \sum_{i=0}^{2} \pi_i P_i(\theta = 2 | F_t^X) \frac{dP_{i,t}}{dP_{\pi,t}} = \pi_2 \frac{dP_{2,t}}{dP_{\pi,t}} = \frac{\pi_2 \frac{dP_{2,t}}{dP_{\pi,t}}}{1 + \pi_1 \frac{dP_{1,t}}{dP_{\pi,t}} + \pi_2 \frac{dP_{2,t}}{dP_{\pi,t}}}
\]

where \(P_{\pi,t}\) denotes the restriction of \(P_{\pi}\) to \(F_t^X\) for \(\pi = (\pi_0, \pi_1, \pi_2) \in [0, 1]^3\) with \(\pi_0 + \pi_1 + \pi_2 = 1\) and \(t \geq 0\). It is then easily verified that (4.6)-(4.8) imply (4.3)-(4.5) as claimed.

3. Previous arguments suggest that changing the probability measure \(P_{\pi}\) to \(P_0\) appears to be of canonical interest in the optimal stopping problem (3.8). In the sequel we let \(P_{\pi,\tau}\) denote the restriction of \(P_{\pi}\) to \(F_{\tau}^X\) where \(\tau\) is a stopping time of \(X\).

**Lemma 1.** The following identity holds

\[
\frac{dP_{\pi,\tau}}{dP_{0,\tau}} = \frac{\pi_0}{\Pi_0^\tau}
\]

for all stopping times \(\tau\) of \(X\) and all \(\pi = (\pi_0, \pi_1, \pi_2) \in [0, 1]^3\) with \(\pi_0 + \pi_1 + \pi_2 = 1\).
Proof. Using the same arguments as in (4.6) above we find that

\begin{equation}
\Pi_t^0 = P_\pi(\theta = 0 \mid \mathcal{F}_t^X) = \sum_{i=0}^{2} \pi_i P_i(\theta = 0 \mid \mathcal{F}_t^X) \frac{dP_{i,t}}{dP_{\pi,t}} = \pi_0 \frac{dP_{0,t}}{dP_{\pi,t}}
\end{equation}

for any \( \tau \) and \( \pi \) as above. From (4.10) we see that (4.9) holds and the proof is complete.

4. We now show that the optimal stopping problem (3.8) admits a transparent reformulation under the probability measure \( P_0 \) in terms of the process \( \Phi = (\Phi^1, \Phi^2) \) defined in (4.3) above. Recall that \( \Phi^i \) starts at \( \pi_i/P_0 \) and this dependence on the initial point will be indicated by a superscript \( \pi_i/P_0 \) to \( \Phi \) replacing its coordinate superscript \( i \) for \( i = 1, 2 \) when needed.

**Proposition 2.** The value function \( V \) from (3.8) satisfies the identity

\begin{equation}
V(\pi) = \pi_0 \hat{V}(\frac{\pi_1}{\pi_0}, \frac{\pi_2}{\pi_0})
\end{equation}

where the value function \( \hat{V} \) is given by

\begin{equation}
\hat{V}(\frac{\pi_1}{\pi_0}, \frac{\pi_2}{\pi_0}) = \inf_{\tau} E_0\left[ \int_0^\tau (1+\Phi^{\sigma_1/\sigma_0}+\Phi^{\sigma_2/\sigma_0}) dt + \hat{M}(\Phi^{\sigma_1/\sigma_0}, \Phi^{\sigma_2/\sigma_0}) \right]
\end{equation}

for \( \pi = (\pi_0, \pi_1, \pi_2) \in [0,1]^3 \) with \( \pi_0+\pi_1+\pi_2 = 1 \) where

\begin{equation}
\hat{M}(\varphi_1, \varphi_2) = c((\varphi_1+\varphi_2) \wedge (1+\varphi_1) \wedge (1+\varphi_2))
\end{equation}

for \( (\varphi_1, \varphi_2) \in [0,\infty)^2 \) and the infimum in (4.12) is taken over all stopping times \( \tau \) of \( X \).

**Proof.** For \( \pi = (\pi_0, \pi_1, \pi_2) \in [0,1]^3 \) with \( \pi_0+\pi_1+\pi_2 = 1 \) given and fixed, it is enough to show that the following identity holds

\begin{equation}
E_\pi[\tau + M(\Pi_\tau)] = \pi_0 E_0\left[ \int_0^\tau (1+\Phi^{\pi_1/\sigma_0}+\Phi^{\pi_2/\sigma_0}) dt + \hat{M}(\Phi^{\pi_1/\sigma_0}, \Phi^{\pi_2/\sigma_0}) \right]
\end{equation}

for all bounded stopping times \( \tau \) of \( X \). For this, suppose that such a stopping time \( \tau \) is given and fixed, and note by (4.5)-(4.9) that

\begin{equation}
E_\pi[\tau + M(\Pi_\tau)] = \pi_0 E_0\left[ \frac{\tau}{\Pi_\tau^0} + \frac{M(\Pi_\tau)}{\Pi_\tau^0} \right]
= \pi_0 E_0\left[ \tau(1+\Phi^{\pi_1/\sigma_0}+\Phi^{\pi_2/\sigma_0}) + \hat{M}(\Phi^{\pi_1/\sigma_0}, \Phi^{\pi_2/\sigma_0}) \right].
\end{equation}

Setting \( M_t = 1+\Phi^{\pi_1/\sigma_0}+\Phi^{\pi_2/\sigma_0} \) for \( t \geq 0 \) we see by (4.2) and (4.4) that \( M = (M_t)_{t \geq 0} \) is a continuous martingale under \( P_0 \) so that integration by parts gives

\begin{equation}
tM_t = \int_0^t M_s \, ds + \int_0^t s \, dM_s
\end{equation}

where the final term defines a continuous martingale under \( P_0 \) for \( t \geq 0 \). Hence by the optional sampling theorem we obtain

\begin{equation}
E_0(\tau M_\tau) = E_0(\int_0^\tau M_t \, dt).
\end{equation}

Inserting this back into (4.15) we obtain (4.14) as claimed and the proof is complete.
5. Elliptic PDE

In this section we derive a coupled system of stochastic differential equations (driven by two independent Brownian motions) that $\Phi = (\Phi^1, \Phi^2)$ solves. From this system we derive a closed-form expression for the infinitesimal generator of $\Phi$ that can be recognised as a partial differential operator of elliptic type. We also show that a diffeomorphic transformation of logarithmic type maps the process $\Phi$ (and its state space $[0, \infty)^2$) to a process $Z$ (and its state space $\mathbb{R}^2$) whose coordinate processes $Z^1$ and $Z^2$ are independent Brownian motions with a non-zero and zero drift respectively.

1. From (4.2) and (4.4) we see that
\begin{equation}
\Phi_1^t = e^{\mu(B^1_t - B^0_t) - \mu^2 t} \quad \& \quad \Phi_2^t = e^{\mu(B^2_t - B^0_t) - \mu^2 t}
\end{equation}
under $P_0$ for $t \geq 0$ where $\varphi_1$ and $\varphi_2$ belong to $[0, \infty)$. Hence by Itô’s formula we find that
\begin{align}
\begin{aligned}
d\Phi_1^t &= \mu \Phi_1^t (dB^1_t - dB^0_t) \\
d\Phi_2^t &= \mu \Phi_2^t (dB^2_t - dB^0_t)
\end{aligned}
\end{align}
under $P_0$ with $\Phi_0^1 = \varphi_1$ and $\Phi_0^2 = \varphi_2$ in $[0, \infty)$. This shows that $\Phi^1$ and $\Phi^2$ are two correlated geometric Brownian motions.

2. A well-known (and easily verifiable) fact states that if $\tilde{B}^1$ and $\tilde{B}^2$ are two correlated standard Brownian motions satisfying $E(\tilde{B}^1_0 \tilde{B}^2_0) = \rho t$ for $t \geq 0$ with $\rho \in (-1, 1)$, then $(\tilde{B}^1 + \tilde{B}^2)/\sqrt{2(1+\rho)}$ and $(\tilde{B}^1 - \tilde{B}^2)/\sqrt{2(1-\rho)}$ are two independent standard Brownian motions. Applying this implication to $\tilde{B}^1 := (B^1 - B^0)/\sqrt{2}$ and $\tilde{B}^2 := (B^2 - B^0)/\sqrt{2}$ with $\rho = 1/2$ it follows that
\begin{equation}
\begin{aligned}
W^1 := \frac{\tilde{B}^1 + \tilde{B}^2}{\sqrt{3}} &= \frac{B^1 + B^2 - 2B^0}{\sqrt{6}} \quad \& \quad W^2 := \frac{\tilde{B}^1 - \tilde{B}^2}{1} &= \frac{B^1 - B^2}{\sqrt{2}}
\end{aligned}
\end{equation}
are two independent standard Brownian motions. From (5.4) we see that
\begin{align}
\begin{aligned}
\tilde{B}^1 := \frac{B^1 - B^0}{\sqrt{2}} &= \frac{\sqrt{3}W^1 + W^2}{2} \quad \& \quad \tilde{B}^2 := \frac{B^2 - B^0}{\sqrt{2}} &= \frac{\sqrt{3}W^1 - W^2}{2}
\end{aligned}
\end{align}
3. Making use of (5.5) in (5.2)+(5.3) we obtain

\[ d\Phi_1^t = \frac{\mu}{\sqrt{2}} \Phi_1^t (\sqrt{3}dW_1^t + dW_2^t) \]

\[ d\Phi_2^t = \frac{\mu}{\sqrt{2}} \Phi_2^t (\sqrt{3}dW_1^t - dW_2^t) \]

with \( \Phi_0^1 = \varphi_1 \) and \( \Phi_0^2 = \varphi_2 \) in \([0, \infty)\). This is a coupled system of stochastic differential equations (driven by two independent standard Brownian motions \( W^1 \) and \( W^2 \)) that \( \Phi^1 \) and \( \Phi^2 \) solve (strongly) and this solution is pathwise unique (see e.g. [20, pp 128-131]). Moreover, the solution \( \Phi = (\Phi^1, \Phi^2) \) is both a strong Markov process (see e.g. [20, pp 158-163]) and a strong Feller process (see e.g. [20, pp 170-173]). Making use of (5.5) in (5.1) we see that

\[ \Phi_1^t = \varphi_1 e^{\frac{\mu}{\sqrt{2}} (\sqrt{3}W_1^t - \varphi_2 W_2^t) - \mu^2 t} \]

\[ \Phi_2^t = \varphi_2 e^{\frac{\mu}{\sqrt{2}} (\sqrt{3}W_1^t + \varphi_2 W_2^t) - \mu^2 t} \]

under \( P_0 \) for \( t \geq 0 \) where \( \varphi_1 \) and \( \varphi_2 \) belong to \([0, \infty)\). Often we will write \( \Phi^1_{\varphi_1} \) and \( \Phi^2_{\varphi_2} \) for \( t \geq 0 \) to indicate dependence of \( \Phi^1 \) and \( \Phi^2 \) on the initial points \( \varphi_1 \) and \( \varphi_2 \) in \([0, \infty)\).

4. Knowing that \( \Phi = (\Phi^1, \Phi^2) \) solves the system (5.6)+(5.7) and making use of Itô’s calculus we find that the infinitesimal generator of \( \Phi \) is given by

\[ \mathcal{L}_{\Phi} = \mu^2 (\varphi_1^2 \partial^2_{\varphi_1 \varphi_1} + \varphi_1 \varphi_2 \partial^2_{\varphi_1 \varphi_2} + \varphi_2^2 \partial^2_{\varphi_2 \varphi_2}) \]

for \( \varphi_1 \) and \( \varphi_2 \) in \((0, \infty)\) (see e.g. (2.7) in [16]). A standard classification of partial differential equations shows that \( \mathcal{L}_{\Phi} \) is of elliptic type (see e.g. (2.12) in [16]).

5. Defining a diffeomorphic transformation of \((0, \infty)^2\) to \( \mathbb{R}^2 \) by

\[ D(\varphi_1, \varphi_2) = (\log(\varphi_1 \varphi_2), \log(\varphi_1 / \varphi_2)) \]

for \((\varphi_1, \varphi_2) \in (0, \infty)^2\), and setting

\[ Z = (Z_1^1, Z_2^2) = D(\Phi_1, \Phi_2) = (\log(\Phi_1 \Phi_2), \log(\Phi_1 / \Phi_2)) \]

we see from (5.8) that

\[ Z_1^1 = Z_0^1 - 2\mu^2 t + \sqrt{6} \mu W_1^t \quad \& \quad Z_2^2 = Z_0^2 + \sqrt{2} \mu W_2^t \]

under \( P_0 \) for \( t \geq 0 \) with \( Z_0^1 = \log(\varphi_1 \varphi_2) \) and \( Z_0^2 = \log(\varphi_1 / \varphi_2) \). This establishes a one-to-one correspondence between the process \( \Phi \) in \((0, \infty)^2\) and the process \( Z \) in \( \mathbb{R}^2 \). Although the latter process \( Z \) may be viewed as a canonical building block which further clarifies the underlying setting, we will mainly study the optimal stopping problem (4.18) by means of the former process \( \Phi \) in the sequel.

6. Lagrange and Mayer formulations

The optimal stopping problem (4.18) is Bolza formulated. In this section we derive its Lagrange and Mayer reformulations which are helpful in the subsequent analysis of the problem.
1. We first consider the Lagrange reformulation of the optimal stopping problem (4.18). For this, note that the loss function $\hat{M}$ from (4.13) that appears on the right-hand side of (4.18) is not smooth at the three straight lines

\begin{align}
(6.1) & \quad \Delta_0 = \{(\varphi_1, \varphi_2) \in [0, \infty)^2 \mid \varphi_1 = 1 \land \varphi_2 \in [0, 1]\} \\
(6.2) & \quad \Delta_1 = \{(\varphi_1, \varphi_2) \in [0, \infty)^2 \mid \varphi_1 \in [0, 1] \land \varphi_2 = 1\} \\
(6.3) & \quad \Delta_2 = \{(\varphi_1, \varphi_2) \in [0, \infty)^2 \mid \varphi_1 = \varphi_2 \in [1, \infty)\}
\end{align}

ordered clockwise (see Figure 1 below). Note moreover that $\hat{M}$ is linear off the three straight lines and given by

\begin{align}
(6.4) & \quad \hat{M}(\varphi_1, \varphi_2) = c(\varphi_1 + \varphi_2) \text{ for } (\varphi_1, \varphi_2) \in \Delta_0 \nonumber \\
& \quad = c(1 + \varphi_1) \text{ for } (\varphi_1, \varphi_2) \in \Delta_1 \nonumber \\
& \quad = c(1 + \varphi_2) \text{ for } (\varphi_1, \varphi_2) \in \Delta_2 \nonumber
\end{align}

where $\Delta_0 := [0, 1]^2$ is a subset of the state space surrounded by $c_0$ and $c_1$ (from the right and above), $\Delta_1 := \{(\varphi_1, \varphi_2) \in [0, \infty)^2 \mid \varphi_2 \geq \varphi_1 \geq 1\}$ is a subset of the state space surrounded by $c_1$ and $c_2$ (from below and the right), and $\Delta_2 := \{(\varphi_1, \varphi_2) \in [0, \infty)^2 \mid \varphi_1 \geq \varphi_2 \geq 1\}$ is a subset of the state space surrounded by $c_0$ and $c_2$ (from the left and above).

**Proposition 3.** The value function $\hat{V}$ from (4.18) can be expressed as

\begin{align}
(6.5) & \quad \hat{V}(\varphi_1, \varphi_2) = \inf_{\tau} \mathbb{E}_{\varphi_1, \varphi_2}^{0} \left[ \int_{0}^{\tau} (1 + \Phi_1 t + \Phi_2 t) \, dt - \frac{c}{2} \left( \ell_\tau^0(\Phi) + \ell_\tau^1(\Phi) + \ell_\tau^2(\Phi) \right) \right] + \hat{M}(\varphi_1, \varphi_2) \\
& \quad \text{for } (\varphi_1, \varphi_2) \in [0, \infty)^2 \text{ where } \ell_i(\Phi) \text{ is the local time of } \Phi \text{ at } c_i \text{ for } i = 0, 1, 2 \text{ given by}
\end{align}

\begin{align}
(6.6) & \quad \ell_0^0(\Phi) = \mathbb{P} - \lim_{\epsilon \to 0} \frac{1}{2\epsilon} \int_{0}^{\tau} I(1 - \epsilon < \Phi_1 t < 1 + \epsilon) I(0 \leq \Phi_2 t \leq 1) \, d\langle \Phi_1, \Phi_1 \rangle_t \\
(6.7) & \quad \ell_1^0(\Phi) = \mathbb{P} - \lim_{\epsilon \to 0} \frac{1}{2\epsilon} \int_{0}^{\tau} I(1 - \epsilon < \Phi_2 t < 1 + \epsilon) I(0 \leq \Phi_1 t \leq 1) \, d\langle \Phi_2, \Phi_2 \rangle_t \\
(6.8) & \quad \ell_2^0(\Phi) = \mathbb{P} - \lim_{\epsilon \to 0} \frac{1}{2\epsilon} \int_{0}^{\tau} I(- \epsilon < \Phi_1 t - \Phi_2 t < \epsilon) I(\Phi_1 t \geq 1, \Phi_2 t \geq 1) \, d\langle \Phi_2 - \Phi_1, \Phi_2 - \Phi_1 \rangle_t
\end{align}

and the infimum in (6.5) is taken over all stopping times $\tau$ of $\Phi$.

**Proof.** It is evident from (6.4) that $\hat{M}$ restricted to $\Delta_0 \cup \Delta_2$ can be extended to a twice continuously differentiable function $\hat{F}$ on $[0, \infty)^2 \setminus c_0$. Then $\hat{M} = \hat{F} + (\hat{M} - \hat{F})$ and $\hat{M}^1 := \hat{F}$ is not smooth at $c_0$ while $\hat{M}^2 := \hat{M} - \hat{F}$ is not smooth at $c_1$ and $c_2$. Since $c_0$ is the graph of a (linear) function of $\varphi_2$, and $c_1$ and $c_2$ are the graphs of (linear) functions of $\varphi_1$, we see that the change-of-variable formula with local time on surfaces [15, Theorem 2.1] is applicable to $\hat{M}^1$ and $\hat{M}^2$ composed with $\Phi$, where we note that $\hat{M}^1_{\varphi_1}(\varphi_1, \varphi_2) - \hat{M}^1_{\varphi_1}(\varphi_1 -, \varphi_2) = -c$ for $(\varphi_1, \varphi_2) \in c_0$ and $\hat{M}^2_{\varphi_2}(\varphi_1, \varphi_2 +) - \hat{M}^2_{\varphi_2}(\varphi_1, \varphi_2 -) = -c$ for $(\varphi_1, \varphi_2) \in c_1 \cup c_2$. Hence the formula is also applicable to $\hat{M}$ composed with $\Phi$ and this gives

\begin{align}
(6.9) & \quad \hat{M}(\Phi_1, \Phi_2) = \hat{M}(\varphi_1, \varphi_2) + c \int_{0}^{\tau} I(\Phi_s \in \Delta_0 \cup \Delta_1) \, d\Phi_1^s + c \int_{0}^{\tau} I(\Phi_s \in \Delta_0 \cup \Delta_2) \, d\Phi_2^s
\end{align}

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for \((\varphi_1, \varphi_2) \in [0, \infty)^2\) and \(t \geq 0\) where the local times are defined in (6.6)-(6.8) above. Since \(\Phi^1\) and \(\Phi^2\) are continuous martingales under \(P_0\), we see that the two integrals on the right-hand side of (6.9) are continuous martingales under \(P_0\) as well. By the optional sampling theorem we therefore find from (6.9) that

\[
(6.10) \quad E_{\varphi_1,\varphi_2}^0[\hat{M}(\varphi_1, \varphi_2)] = \hat{M}(\varphi_1, \varphi_2) - \frac{c}{2}E_{\varphi_1,\varphi_2}^0[\ell_t^0(\Phi) + \ell_t^1(\Phi) + \ell_t^2(\Phi)]
\]

for all \((\varphi_1, \varphi_2) \in [0, \infty)^2\) and all stopping times \(\tau\) of \(\Phi\). Inserting (6.10) into (4.18) we obtain (6.5) as claimed and the proof is complete. \(\Box\)

The Lagrange reformulation (6.5) of the optimal stopping problem (4.18) reveals the underlying rationale for continuing vs stopping in a clearer manner. Indeed, recalling that the local time process \(t \mapsto \ell_t^0(\Phi)\) strictly increases only when \(\Phi\) is at \(c_1\), and that \(\ell_t^0(\Phi) \sim \sqrt{t}\) is strictly larger than \(\int_0^1 (1 + \varphi_2^2 + \varphi_2^3) ds \sim t\) for small \(t\), we see from (6.5) that it should never be optimal to stop at \(c_1\) and the incentive for stopping should increase the further away \(\Phi\) gets from \(c_i\) for \(i = 0, 1, 2\). We will see in Section 8 below that these informal conjectures can be formalised and this will give a proof of the fact that the three straight lines \(c_0, c_1, c_2\) are contained in the continuation set of the optimal stopping problem (4.18).

2. We next consider the Mayer reformulation of the optimal stopping problem (4.18). For this, in addition to \(\hat{M}\) in (4.13) above, define

\[
(6.11) \quad \hat{M}(\varphi_1, \varphi_2) = \frac{1}{\mu^2} \left( \varphi_1(\log \varphi_1 - 1) + \varphi_2(\log \varphi_2 - 1) - \frac{1}{2} \log(\varphi_1 \varphi_2) \right)
\]

and set \(M(\varphi_1, \varphi_2) = \hat{M}(\varphi_1, \varphi_2) + \hat{M}(\varphi_1, \varphi_2)\) for \((\varphi_1, \varphi_2) \in (0, \infty)^2\).

**Proposition 4.** The value function \(\hat{V}\) from (4.18) can be expressed as

\[
(6.12) \quad \hat{V}(\varphi_1, \varphi_2) = \inf_{\tau} E_{\varphi_1,\varphi_2}^0[M(\varphi_1, \varphi_2)] - \hat{M}(\varphi_1, \varphi_2)
\]

for \((\varphi_1, \varphi_2) \in (0, \infty)^2\) where the infimum is taken over all stopping times \(\tau\) of \(\Phi\).

**Proof.** Recalling the closed-form expression for \(\mathbb{L}_{\Phi}\) in (5.9) it is easily verified that

\[
(6.13) \quad \mathbb{L}_{\Phi} \hat{M}(\varphi_1, \varphi_2) = 1 + \varphi_1 + \varphi_2
\]

for \((\varphi_1, \varphi_2) \in (0, \infty)^2\). By Itô’s formula we thus find using (5.6)+(5.7) above that

\[
(6.14) \quad \hat{M}(\varphi_1, \varphi_2) = \hat{M}(\varphi_1, \varphi_2) + \int_0^t \hat{M}(\varphi_1, \varphi_2) d\Phi_1 + \int_0^t \hat{M}(\varphi_1, \varphi_2) d\Phi_2
\]

\[
+ \int_0^t \mathbb{L}_{\Phi} \hat{M}(\varphi_1, \varphi_2) ds = \hat{M}(\varphi_1, \varphi_2) + \int_0^t \frac{1}{\sqrt{2\mu}} (\varphi_1 \log \varphi_1 - \frac{1}{2}) (\sqrt{3} dW_1 + dW_2)
\]

\[
+ \int_0^t \frac{1}{\sqrt{2\mu}} (\varphi_2 \log \varphi_2 - \frac{1}{2}) (\sqrt{3} dW_1 - dW_2) + \int_0^t (1 + \varphi_1 + \varphi_2) ds
\]

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for \((\varphi_1, \varphi_2) \in (0, \infty)^2\) and \(t \geq 0\) where the two integrals on the right-hand side define continuous local martingales under \(P_0\). Making use of a localisation sequence of stopping times for these two local martingales if needed, and applying the optional sampling theorem, we find from (6.14) that

\[
E^0_{\varphi_1, \varphi_2} \left[ \tilde{M}(\Phi^1_t, \Phi^2_t) \right] = \tilde{M}(\varphi_1, \varphi_2) + E^0_{\varphi_1, \varphi_2} \left[ \int_0^T (1 + \Phi^1_t + \Phi^2_t) \, dt \right]
\]

for all \((\varphi_1, \varphi_2) \in (0, \infty)^2\) and all (bounded) stopping times \(\tau\) of \(\Phi\). Inserting (6.15) into (4.18) we obtain (6.12) as claimed and the proof is complete. \(\square\)

7. Two dimensions

The observed process \(X\) in the initial sequential testing problem (3.3) is three-dimensional. In this section we consider the analogue of (3.3) and the resulting optimal stopping problem (4.18) when \(X\) is two-dimensional. The reduction of dimension three to dimension two corresponds to either \(\Phi^1\) or \(\Phi^2\) becoming 0 which is a natural boundary point for both processes (cf. [6]). This shows that \(\Phi\) is a one-dimensional Markov/diffusion process when \(X\) is two-dimensional so that standard arguments enable us to solve the problem (4.18) in a closed form. The derived results for the one-dimensional optimal stopping problem (4.18) when \(X\) is two-dimensional will be used in the subsequent analysis of the two-dimensional optimal stopping problem (4.18) when \(X\) is three-dimensional.

1. Using the same arguments as above, it is easily seen that the sequential testing problem (3.3) when \(X\) is two-dimensional reduces to the optimal stopping problem (4.18) with \(\Phi^2\) being formally equal to zero. Omitting the subscript 1 from \(\varphi_1\) for simplicity, we thus see that the optimal stopping problem (4.18) reads

\[
\hat{V}(\varphi) = \inf_\tau E^0_{\varphi} \left[ \int_0^\tau (1 + \Phi_t) \, dt + c(1 \wedge \Phi_\tau) \right]
\]

for \(\varphi \in [0, \infty)\) with \(P^0_\varphi(\Phi_0 = \varphi) = 1\) where the infimum in (7.1) is taken over all stopping times \(\tau\) of \(\Phi\). From (5.1) and (5.2) we see that

\[
\Phi_t = \varphi e^{\sqrt{2} \mu W_t - \mu^2 t}
\]

\[
d\Phi_t = \sqrt{2} \mu \Phi_t \, dW_t
\]

under \(P_0\) for \(t \geq 0\) with \(\Phi_0 = \varphi\) in \([0, \infty)\) where \(W := (B^1 - B^0)/\sqrt{2}\) is a standard Brownian motion. From (7.3) we see that the infinitesimal generator of \(\Phi\) is given by

\[
\mathcal{L}_\Phi = \mu^2 \varphi^2 \frac{d^2}{d\varphi^2}
\]

which also follows formally by setting \(\varphi_2 = 0\) in (5.9) above.

Recognising the loss function in (7.1) as \(\tilde{M}(\varphi) = c(1 \wedge \varphi)\) for \(\varphi \in [0, \infty)\), standard arguments imply (see e.g. [17]) that \(\hat{V}\) should solve the free-boundary problem

\[
\mathcal{L}_\Phi \hat{V}(\varphi) = -(1 + \varphi) \text{ for } \varphi \in (\varphi_0^*, \varphi_1^*)
\]
\[ V(\varphi^*_i) = \dot{M}(\varphi^*_i) \quad \text{for} \quad i = 0, 1 \quad \text{(instantaneous stopping)} \]

\[ \dot{V}'(\varphi^*_i) = \dot{M}'(\varphi^*_i) \quad \text{for} \quad i = 0, 1 \quad \text{(smooth fit)} \]

where \( 0 < \varphi^*_0 < 1 < \varphi^*_1 < \infty \) are the optimal stopping/boundary points to be found and we have \( \hat{V}(\varphi) = \hat{M}(\varphi) \) for \( \varphi \in [0, \varphi^*_0) \cup (\varphi^*_1, \infty) \) as well (in addition to (7.6) above).

The general solution to the ordinary differential equation (7.5) is given by

\[ \hat{V}(\varphi) = A\varphi + B + \frac{1}{\mu^2} (1 - \varphi) \log \varphi \]

for \( \varphi > 0 \) where \( A \) and \( B \) are two undetermined real constants. Boundary conditions (7.6) and (7.7) then read as follows

\[ A\varphi^*_0 + B + \frac{1}{\mu^2} (1 - \varphi^*_0) \log \varphi^*_0 = c\varphi^*_0 \]
\[ A\varphi^*_1 + B + \frac{1}{\mu^2} (1 - \varphi^*_1) \log \varphi^*_1 = c \]
\[ A + \frac{1}{\mu^2} \left( \frac{1}{\varphi^*_0} - \log \varphi^*_0 - 1 \right) = c \]
\[ A + \frac{1}{\mu^2} \left( \frac{1}{\varphi^*_1} - \log \varphi^*_1 - 1 \right) = 0. \]

It is a matter of routine to verify that the system (7.9)-(7.12) has a unique solution given by

\[ A^* = c - \frac{1}{\mu^2} \left( \frac{1}{\varphi^*_0} - \log \varphi^*_0 - 1 \right) \quad \& \quad B^* = c - \frac{1}{\mu^2} \left( \varphi^*_1 + \log \varphi^*_1 - 1 \right) \]

where \( \varphi^*_0 \) and \( \varphi^*_1 \) are the unique solution to

\[ \frac{1}{\mu^2} \left( \frac{1}{\varphi^*_0} - \frac{1}{\varphi^*_1} + \log \left( \frac{\varphi^*_1}{\varphi^*_0} \right) \right) = c \quad \& \quad \frac{1}{\mu^2} \left( \varphi^*_1 - \varphi^*_0 + \log \left( \frac{\varphi^*_1}{\varphi^*_0} \right) \right) = c \]

satisfying \( 0 < \varphi^*_0 < 1 < \varphi^*_1 < \infty \).

By symmetry we may conclude that \( \varphi^*_0 = 1/\varphi^*_1 \) so that (7.13) and (7.14) reduce to

\[ A^* = B^* = c - \frac{1}{\mu^2} \left( \varphi^*_1 + \log \varphi^*_1 - 1 \right) \]
\[ \varphi^*_1 - \frac{1}{\varphi^*_1} + 2 \log \varphi^*_1 = c\mu^2 \]

respectively. It follows from (7.8) and (7.15) that

\[ \hat{V}^*(\varphi) = \left( c - \frac{1}{\mu^2} \left( \varphi^*_1 + \log \varphi^*_1 - 1 \right) \right) (1 + \varphi) + \frac{1}{\mu^2} (1 - \varphi) \log \varphi \quad \text{for} \quad \varphi \in \left( 1/\varphi^*_1, \varphi^*_1 \right) \]
\[ = \hat{M}(\varphi) \quad \text{for} \quad \varphi \in [0, 1/\varphi^*_1] \cup [\varphi^*_1, \infty) \]

defines a candidate value function for the optimal stopping problem (7.1).

Applying the Itô-Tanaka formula (cf. [19, p. 223]) to \( \hat{V}^* \) composed with \( \Phi \), which reduces to Itô’s formula due to smooth fit (7.7), and making use of the optional sampling theorem, it
is easily verified that \( \hat{V}^* \) from (7.17) coincides with the value function \( \hat{V} \) from (7.1) and the optimal stopping time (at which the infimum in (7.1) is attained) is given by

\[
(7.18) \quad \tau_* = \inf \{ t \geq 0 \mid \Phi_t \notin (1/\varphi_1^*, \varphi_1^*) \}
\]

where \( \varphi_1^* \) is the unique solution to (7.16) on \((1, \infty)\).

To avoid a possible confusion with subscripts we will set \( \beta := \varphi_1^* \) in the sequel. Thus \( \beta \in (0, \infty) \) is the unique solution to

\[
(7.19) \quad \beta - \frac{1}{\beta} + 2 \log \beta = c\mu^2
\]

and the stopping time

\[
(7.20) \quad \tau = \inf \{ t \geq 0 \mid \Phi_t \notin (\alpha, \beta) \}
\]

is optimal in (7.1) where we set \( \alpha = 1/\beta \). These facts will be used in the subsequent analysis of the optimal stopping problem (4.18) when \( X \) is three-dimensional.

8. Properties of the optimal stopping boundaries

In this section we establish the existence of an optimal stopping time in (4.18) when the observed process \( X \) is three-dimensional and derive basic properties of the optimal stopping boundaries. These results will be further refined in Section 10 below.

1. Looking at (4.18) we may conclude that the (candidate) continuation and stopping sets in this problem are respectively given by

\[
(8.1) \quad C = \{ (\varphi_1, \varphi_2) \in [0, \infty)^2 \mid \hat{V}(\varphi_1, \varphi_2) < \hat{M}(\varphi_1, \varphi_2) \}
\]

\[
(8.2) \quad D = \{ (\varphi_1, \varphi_2) \in [0, \infty)^2 \mid \hat{V}(\varphi_1, \varphi_2) = \hat{M}(\varphi_1, \varphi_2) \}
\]

where \( \hat{M} \) is defined in (4.13) above. Recalling (5.8) we see that the expectation in (6.12) defines a continuous function of the initial point \( (\varphi_1, \varphi_2) \) in \([0, \infty)^2\) for every (bounded) stopping time \( \tau \) of \( \Phi \) given and fixed. Taking the infimum over all (bounded) stopping times \( \tau \) of \( \Phi \) we can conclude that the value function \( \hat{V} \) is upper semicontinuous on \([0, \infty)^2\). From (4.13) and (6.11) we see that the loss function \( M = \hat{M} + \hat{M} \) is continuous and hence lower semicontinuous on \([0, \infty)^2\). It follows therefore by [17, Corollary 2.9] that the first entry time of the process \( \Phi \) into the closed set \( D \) defined by

\[
(8.3) \quad \tau_D = \inf \{ t \geq 0 \mid \Phi_t \in D \}
\]

is optimal in (6.12), and hence in (4.18) as well, whenever \( P_0^{\varphi_1, \varphi_2}(\tau_D < \infty) = 1 \) for all \((\varphi_1, \varphi_2) \in [0, \infty)^2\). In the sequel we will establish this and other properties of \( \tau_D \) by analysing the boundary of \( D \). We first turn to global properties of the value function \( \hat{V} \) itself.

**Proposition 5.** For the value function \( \hat{V} \) from (4.18) we have

\[
(8.4) \quad (\varphi_1, \varphi_2) \mapsto \hat{V}(\varphi_1, \varphi_2) \text{ is concave on } [0, \infty)^2
\]
\begin{equation}
(\varphi_1, \varphi_2) \mapsto \hat{V}(\varphi_1, \varphi_2) \text{ is continuous on } [0, \infty)^2.
\end{equation}

\textbf{Proof.} We first show that (8.4) is satisfied. Combining (5.8) with the concavity of the loss function $\hat{M}$ from (4.13) we see that the expectation in (4.18) defines a concave function of the initial point $(\varphi_1, \varphi_2)$ in $[0, \infty)^2$ for every (bounded) stopping time $\tau$ of $\Phi$ given and fixed. Taking the infimum over all (bounded) stopping times $\tau$ of $\Phi$ we find that the value function $\hat{V}$ itself is concave as claimed in (8.4) above.

We next show that (8.5) is satisfied. From the concavity of $\hat{V}$ on the open set $(0, \infty)^2$ we can conclude that $\hat{V}$ is continuous on $(0, \infty)^2$. Recall that there are concave functions $F$ defined on a convex subset $S$ of $\mathbb{R}^2$ and taking values in $\mathbb{R}$, such that the limit of $F(x_n)$ may not exist when $x_n$ belonging to the interior of $S$ converges to a point $x_0$ at the boundary of $S$ as $n \to \infty$. However, if $S$ is closed then it is well known (and easily verified) that such a function $F$ must be lower semicontinuous. Applying this implication to $F = \hat{V}$ and $S = [0, \infty)^2$ we can conclude that $\hat{V}$ is lower semicontinuous on $[0, \infty)^2$. At the same time we know that $\hat{V}$ is upper semicontinuous (as established following (8.2) above) and hence we can conclude that $\hat{V}$ is continuous as claimed in (8.5) above. \hfill \Box

2. We show that the three straight lines $c_0, c_1, c_2$ defined in (6.1)-(6.3) above are contained in the continuation set $C$. The proof of this fact uses the Lagrange reformulation (6.5) of the optimal stopping problem (4.18) combined with the fact that the local times in (6.5) have a square-root growth at the three straight lines while the integral in (6.5) grows linearly.

\textbf{Proposition 6.} \textit{The straight lines }$c_0, c_1, c_2$ \textit{from (6.1)-(6.3) are contained in the continuation set }$C$ \textit{of the optimal stopping problem (4.18).}

\textbf{Proof.} We claim that
\begin{equation}
E_{\varphi_1, \varphi_2}^0 [\ell_{t \wedge \tau_R}^i] \geq \kappa_i \sqrt{t}
\end{equation}
for all $t \in (0, t_i)$ with some $\kappa_i > 0$ and $t_i > 0$ for $i = 0, 1, 2$ where $\tau_R = \inf \{ t \geq 0 \mid (\Phi_1, \Phi_2) \notin R \}$ is the first exit time of $\Phi$ from a bounded rectangle $R$ containing the given point $(\varphi_1, \varphi_2) \in c_0 \cup c_1 \cup c_2$ in its interior. Indeed, this follows by a direct application of Lemma 15 in [16] when $(\varphi_1, \varphi_2)$ belongs to $c_0 \cup c_1$, while the same lemma is applicable to $(\Phi_1, \Phi_2) := (\Phi_2 - \Phi_1, \Phi_2 + \Phi_1)$ obtained by a (bijective) clockwise rotation of $(\varphi_1, \varphi_2)$ for 45° when $(\varphi_1, \varphi_2)$ belongs to $c_2$. Note that the case when $(\varphi_1, \varphi_2) = (1, 1) \in c_0 \cap c_1 \cap c_2$ presents no difficulty as the proof of Lemma 15 in [16] extends plainly to cover this case as well. Having (8.6) in place we can then proceed as follows.

For $(\varphi_1, \varphi_2) \in c_0 \cup c_1 \cup c_2$ given and fixed, set $R = [0, 2\varphi_1] \times [0, 2\varphi_2]$ and consider the stopping time $\tau := t \wedge \tau_R$ for $t \in (0, t_i)$ if $(\varphi_1, \varphi_2)$ belongs to $c_i$ for $i = 0, 1, 2$. Inserting this $\tau$ under the expectation sign in (6.5) and making use of (8.6) we find that
\begin{equation}
\hat{V}(\varphi_1, \varphi_2) \leq (1 + 2\varphi_1 + 2\varphi_2) t - \frac{c}{2} \kappa_i \sqrt{t} + \hat{M}(\varphi_1, \varphi_2)
\end{equation}
for all $t \in (0, t_i)$ if $(\varphi_1, \varphi_2)$ belongs to $c_i$ for $i = 0, 1, 2$. Taking $t$ in (8.7) sufficiently small we see that $\hat{V}(\varphi_1, \varphi_2) \leq \hat{M}(\varphi_1, \varphi_2)$ which shows that $(\varphi_1, \varphi_2)$ belongs to $C$ as claimed. \hfill \Box

3. The three straight lines $c_0, c_1, c_2$ naturally split the stopping set $D$ into the three subsets
\begin{equation}
D_0 = \{ (\varphi_1, \varphi_2) \in D \mid \varphi_1, \varphi_2 \in [0, 1] \}.
\end{equation}
(8.9) \[ D_1 = \{ (\varphi_1, \varphi_2) \in D \mid 1 \leq \varphi_1 \leq \varphi_2 \} \]
(8.10) \[ D_2 = \{ (\varphi_1, \varphi_2) \in D \mid 1 \leq \varphi_2 \leq \varphi_1 \} . \]

Note that the set \( D_0 \) is surrounded by the straight lines \( c_0 \) and \( c_1 \), the set \( D_1 \) is surrounded by the straight lines \( c_1 \) and \( c_2 \), and the set \( D_2 \) is surrounded by the straight lines \( c_0 \) and \( c_2 \). Clearly \( D = D_0 \cup D_1 \cup D_2 \) and the sets \( D_0, D_1, D_2 \) are disjoint (see Figure 1 below).

**Proposition 7.** The sets \( D_0, D_1, D_2 \) are convex.

**Proof.** We will show that the set \( D_2 \) is convex and the same arguments can be used to show that the sets \( D_0 \) and \( D_1 \) are convex. For this, let \( (\varphi'_1, \varphi'_2) \) and \( (\varphi''_1, \varphi''_2) \) belonging to \( D_2 \) and \( \lambda \in (0, 1) \) be given and fixed. Firstly, note that

(8.11) \[ \hat{V}(\lambda(\varphi'_1, \varphi'_2)+(1-\lambda)(\varphi''_1, \varphi''_2)) = \hat{V}(\lambda\varphi'_1+(1-\lambda)\varphi'_2, \lambda\varphi'_2+(1-\lambda)\varphi''_2) \]
\[ \leq \hat{M}(\lambda\varphi'_1+(1-\lambda)\varphi''_1, \lambda\varphi'_2+(1-\lambda)\varphi''_2) \]
\[ = c(1+\lambda\varphi'_2+(1-\lambda)\varphi''_2) \]

where we use (4.13) to infer that \( \hat{M}(\varphi'_1, \varphi'_2) = c(1+\varphi_2) \) for \( (\varphi'_1, \varphi'_2) \) belonging to the subset of \([0, \infty)^2\) surrounded by \( c_0 \) and \( c_2 \). Secondly, using that \( V \) is concave on \([0, \infty)^2\) as established in (8.4) above, we find that

(8.12) \[ \hat{V}(\lambda(\varphi'_1, \varphi'_2)+(1-\lambda)(\varphi''_1, \varphi''_2)) \geq \lambda \hat{V}(\varphi'_1, \varphi'_2)+(1-\lambda)\hat{V}(\varphi''_1, \varphi''_2) \]
\[ = \lambda\hat{M}(\varphi'_1, \varphi'_2)+(1-\lambda)\hat{M}(\varphi''_1, \varphi''_2) \]
\[ = c(1+\lambda\varphi'_2+(1-\lambda)\varphi''_2) \]

where in the first equality we use that \( (\varphi'_1, \varphi'_2) \) and \( (\varphi''_1, \varphi''_2) \) belong to \( D_2 \subseteq D \). Combining (8.11) and (8.12) we see that \( V(\lambda(\varphi'_1, \varphi'_2)+(1-\lambda)(\varphi''_1, \varphi''_2)) = \hat{M}(\lambda(\varphi'_1, \varphi'_2)+(1-\lambda)(\varphi''_1, \varphi''_2)) \)

showing that \( \lambda(\varphi'_1, \varphi'_2)+(1-\lambda)(\varphi''_1, \varphi''_2) \) belongs to \( D_2 \) as needed. \( \square \)

4. To describe the shape of the stopping sets \( D_0, D_1, D_2 \) we may recall from Section 7 that the subsets \( \{(0, 1/\beta) \cup [\beta, \infty)\} \times \{0\} \) and \( \{0\} \times (0, 1/\beta) \cup [\beta, \infty) \) of \([0, \infty)^2\) are contained in \( D \) where \( \beta \in (1, \infty) \) solves (7.19) uniquely. Symmetry arguments to be addressed shortly below show that it is sufficient to focus on the set \( D_2 \) as the conclusions will directly extend to the sets \( D_0 \) and \( D_1 \) as well. Moving from the straight lines \( c_0 \) and \( c_2 \) in \( C \) to the right, let us formally define the (least) boundary between \( C \) and \( D_2 \) by setting

(8.13) \[ b_2(\varphi_2) = \inf \{ \varphi_1 > 1 \mid \varphi_2 \} \mid (\varphi_1, \varphi_2) \in D_2 \} \]

for \( \varphi_2 \in [0, \infty) \). Clearly the infimum in (8.13) is attained since \( D_2 \) is closed. We now show that \( b_2 \) constitutes the entire boundary of \( D_2 \) in \([0, \infty)^2\) (see Figure 1 below).

**Proposition 8.** The mapping \( \varphi_2 \mapsto b_2(\varphi_2) \) is finite valued on \([0, \infty)\) and we have

(8.14) \[ D_2 = \{ (\varphi_1, \varphi_2) \in [0, \infty)^2 \mid \varphi_1 \geq b_2(\varphi_2) \} \]

with \( b_2(0) = \beta \in (1, \infty) \) and \( b_2(\varphi_2) \to \infty \) as \( \varphi_2 \to \infty \).
Proof. To derive (8.14) we show that

\[(8.15) \quad (\varphi', \varphi'') \in D_2 \Rightarrow (\varphi''', \varphi'') \in D_2\]

for all \(\varphi'' \geq \varphi'\). For this, recall from (8.4) that \(\varphi_1 \mapsto \hat{V}(\varphi_1, \varphi_2)\) is concave on \([0, \infty)\) while \(\varphi_1 \mapsto \hat{M}(\varphi_1, \varphi_2) = c(1 + \varphi_2)\) is constant for \(\varphi_1 \geq \varphi_2 \geq 1\). Hence if \(\hat{V}(\varphi_1', \varphi_2') = \hat{M}(\varphi_1', \varphi_2')\) due to \((\varphi_1', \varphi_2') \in D_2\) with \(\hat{V}(\varphi''', \varphi_2'') < \hat{M}(\varphi''', \varphi_2'')\) meaning that \((\varphi''', \varphi'') \notin D_2\) for some \(\varphi''' > \varphi'\), then \(\hat{V}(\varphi_1', \varphi_2')\) must converge to \(-\infty\) as \(\varphi_1\) converges to \(\infty\). This however contradicts the fact that \(\hat{V}\) is non-negative and hence (8.15) must hold as claimed. Combining (8.13) and (8.15) we see that (8.14) is satisfied as claimed.

To establish that \(b_2\) is finite valued we first show that

\[(8.16) \quad (\varphi', \varphi'') \in D_2 \Rightarrow (\varphi', \varphi'') \in D_2\]

for all \(\varphi'' \in [0, \varphi']\) when \(\varphi' > \beta\). (Note that the latter inequality cannot be omitted and (8.16) may fail when \(\varphi' < \beta\) as we will see in Section 10 below.) For this, recall from (8.4) that \(\varphi_2 \mapsto \hat{V}(\varphi_1, \varphi_2)\) is concave on \([0, \infty)\) while \(\varphi_2 \mapsto \hat{M}(\varphi_1, \varphi_2) = c(1 + \varphi_2)\) is linear for \(\varphi_2 \in [1, \varphi']\). By the results of Section 7 we know that \((\varphi', 0)\) belongs to \(D_2\) so that \(\hat{V}(\varphi', 0) = \hat{M}(\varphi', 0)\) when \(\varphi' > \beta\). Hence if \(\hat{V}(\varphi', \varphi_2) = \hat{M}(\varphi', \varphi_2)\) due to \((\varphi', \varphi_2) \in D_2\) then \(\hat{V}(\varphi', \varphi_2) = \hat{M}(\varphi', \varphi_2)\) for all \(\varphi_2 \in [0, \varphi']\). This shows that (8.16) holds as claimed.

From (8.16) we see that if \(b_2(\varphi_2) > \beta\) for some \(\varphi_2 > 0\) then \(b_2(\varphi_2)\) is increasing on \([\varphi_2, \infty)\). In particular, this means that if \(b_2(\varphi_2) = \infty\) for some \(\varphi_2 > 0\) then \(b_2(\varphi_2) = \infty\) for all \(\varphi_2 \geq \varphi_2'\). We will now use this fact to show that \(b_2\) is finite valued as claimed.

Assuming that \(b_2(\varphi_2') = \infty\) for some \(\varphi_2 > 0\), and fixing \(b > a > \varphi_2'\), it follows from the previous argument that the rectangle \(R_N = (N, \infty) \times (a, b)\) is contained in \(C\) for every \(N \geq N_0\) with some \(N_0 \geq 1\) large enough. Consider the stopping time

\[(8.17) \quad \tau_{R_N}^{\varphi_1, \varphi_2} = \inf \{ t \geq 0 \mid (\Phi_t^{\varphi_1}, \Phi_t^{\varphi_2}) \notin R_N \}\]

for \((\varphi_1, \varphi_2) \in R_N\). Since \(R_N \subseteq C\) we see that \(\tau_{R_N}^{\varphi_1, \varphi_2} \leq \tau_D^{\varphi_1, \varphi_2}\) and hence it follows that

\[(8.18) \quad c(1 + \varphi_2) \geq M(\varphi_1, \varphi_2) = \hat{V}(\varphi_1, \varphi_2) = E_0[\varphi_1, \varphi_2] \left[ \int_0^{\tau_{R_N}^{\varphi_1, \varphi_2}} (1 + \Phi_t^{\varphi_1} + \Phi_t^{\varphi_2}) dt + \hat{M}(\Phi_t^{\varphi_1}, \Phi_t^{\varphi_2}) \right] \geq E_0\left[ \int_0^{\tau_{R_N}^{\varphi_1, \varphi_2}} \Phi_t^{\varphi_1} dt \right] \geq N E_0[\tau_{R_N}^{\varphi_1, \varphi_2}]\]

for all \(N \geq N_0\). Noting that \(E_0[\tau_{R_N}^{\varphi_1, \varphi_2}] \to E_0[\tau_{(a,b)\gamma}]\) where \(\tau_{(a,b)\gamma} = \inf \{ t \geq 0 \mid \Phi_t \notin (a, b) \}\) as \(N \to \infty\), we see from (8.18) that

\[(8.19) \quad c(1 + \varphi_2) \geq \frac{N}{2} E_0[\tau_{(a,b)\gamma}]\]

for all \(N \geq N_1\) with some \(N_1 \geq 1\) large enough. Letting \(N \to \infty\) and using that \(E_0[\tau_{(a,b)\gamma}] > 0\) we obtain a contradiction. Thus there is no \(\varphi_2 > 0\) such that \(b_2(\varphi_2) = \infty\) and hence \(b_2\) is finite valued as claimed.

Finally, the fact that \(b_2(0) = \beta \in (1, \infty)\) was established in Section 7 above. Moreover, since \(b_2(\varphi_2) > \varphi_2\) for all \(\varphi_2 > 0\) due to \(c_0\) and \(c_2\) being contained in \(C\), we see that \(b_2(\varphi_2) \to \infty\) as \(\varphi_2 \to \infty\) and the proof is complete. \(\square\)
Proposition 9. The mapping $\varphi_2 \mapsto b_2(\varphi_2)$ is convex and continuous on $[0, \infty)$.

Proof. Convexity of the mapping $\varphi_2 \mapsto b_2(\varphi_2)$ on $[0, \infty)$ follows from the convexity of the stopping set $D_2$ as established in Proposition 7 above. Hence the mapping $\varphi_2 \mapsto b_2(\varphi_2)$ is continuous on $(0, \infty)$ while $b_2$ cannot make a jump at 0 due to the fact that the stopping set $D_2$ is closed. This completes the proof. \hfill $\square$

We will show in Section 10 below that $b_2(\varphi_2) < \beta$ for $\varphi_2 \in (0, \kappa)$ with $\kappa > 0$ such that $b_2(\kappa) = \beta$. This fact combined with the convexity of $b_2$ on $[0, \infty)$ means that the mapping $\varphi_2 \mapsto b_2(\varphi_2)$ is (firstly) decreasing on $[0, \kappa']$ and (then) increasing on $[\kappa', \infty)$ with some $\kappa' \in (0, \kappa)$. In addition to these facts about $b_2$ around zero we will conclude this section by evaluating the asymptotic behaviour of $b_2$ at infinity. Before we do that we will turn to the remaining two stopping sets $D_0$ and $D_1$ including their boundaries.

5. Symmetry arguments enable us to extend the setting and results of Proposition 8 and Proposition 9 from the stopping set $D_2$ to the remaining two stopping sets $D_0$ and $D_1$. For this, recall from (4.3) that $\Phi^1 = \Pi^1/\Pi^0$ and $\Phi^2 = \Pi^2/\Pi^0$. Since $\Pi^0, \Pi^1, \Pi^2$ play a symmetric role in the optimal stopping problem (3.8) we see that any permutation of the three coordinates should yield the same result. There are two generic permutations which generate all the others (six in total). The first generic permutation is obtained by swapping $\Pi^1$ and $\Pi^2$ while keeping $\Pi^0$ intact. This yields $\Phi^1 = \Pi^1/\Pi^0 \sim \Pi^2/\Pi^0 = \Phi^2$ and $\Phi^2 = \Pi^2/\Pi^0 \sim \Pi^1/\Pi^0 = \Phi^1$ showing that

\begin{equation}
(8.20) \quad (\varphi_1, \varphi_2) \in \partial C \iff (\varphi_2, \varphi_1) \in \partial C
\end{equation}

where $\partial C$ can also be replaced by $C$ or $D$. The second generic permutation is obtained by swapping $\Pi^0$ and $\Pi^1$ while keeping $\Pi^2$ intact. This yields $\Phi_1 = \Pi^1/\Pi^0 \sim \Pi^0/\Pi^1 = 1/\Phi^1$ and $\Phi_2 = \Pi^2/\Pi^0 \sim \Pi^2/\Pi^1 = \Phi^2/\Phi^1$ showing that

\begin{equation}
(8.21) \quad (\varphi_1, \varphi_2) \in \partial C \iff \left( \frac{1}{\varphi_1}, \frac{\varphi_2}{\varphi_1} \right) \in \partial C
\end{equation}

where $\partial C$ can also be replaced by $C$ or $D$. The remaining four equivalencies can be obtained by combining (8.20) and (8.21). For example, applying first (8.20) and then (8.21) we find that $(\varphi_1, \varphi_2) \in \partial C \iff (1/\varphi_2, \varphi_1/\varphi_2) \in \partial C$ (where $\partial C$ can also be replaced by $C$ or $D$ as above) which is obtained by swapping $\Pi^0$ and $\Pi^2$ while keeping $\Pi^1$ intact.

6. Having understood the symmetry relations we now move to extending the setting and results of Proposition 8 and Proposition 9 from $D_2$ to $D_0$ and $D_1$. We first address the case of $D_1$ which in view of (8.20) is a mirror image of $D_2$ across the main diagonal in $[0, \infty)^2$. In analogy with (8.13) we thus define the (least) boundary between $C$ and $D_1$ by setting

\begin{equation}
(8.22) \quad b_1(\varphi_1) = \inf \{ \varphi_2 > 1 \vee \varphi_1 \mid (\varphi_1, \varphi_2) \in D_1 \}
\end{equation}

for $\varphi_1 \in [0, \infty)$. Clearly the infimum in (8.22) is attained since $D_1$ is closed. Similarly to $b_2$ and $D_2$ above we now show that $b_1$ constitutes the entire boundary of $D_1$ in $[0, \infty)^2$ (see Figure 1 below).
Proposition 10. The mapping $\varphi_1 \mapsto b_1(\varphi_1)$ is finite valued on $[0, \infty)$ and we have
\begin{equation}
D_1 = \{ (\varphi_1, \varphi_2) \in [0, \infty)^2 \mid \varphi_2 \geq b_1(\varphi_1) \}
\end{equation}
with $b_1(0) = \beta \in (1, \infty)$ and $b_1(\varphi_1) \to \infty$ as $\varphi_1 \to \infty$.

Proof. This can be derived in exactly the same way as in Proposition 8 above. Alternatively Proposition 10 also follows directly from Proposition 8 using the symmetry relation (8.20) which shows that $D_1$ is a mirror image of $D_2$ across the main diagonal in $[0, \infty)^2$. □

Proposition 11. The mapping $\varphi_1 \mapsto b_1(\varphi_1)$ is convex and continuous on $[0, \infty)$.

Proof. This can be derived in exactly the same way as in Proposition 9 above. Alternatively Proposition 11 also follows directly from Proposition 9 using the symmetry relation (8.20) which shows that $b_1$ coincides with $b_2$ on $[0, \infty)$. □

Despite the fact that the functional rules of $b_1$ and $b_2$ coincide on $[0, \infty)$, we will still keep their different subscripts 1 and 2 in place to account for different arguments in $(\varphi_1, b_1(\varphi_1))$ and $(b_2(\varphi_2), \varphi_2)$ for $\varphi_1 \geq 0$ and $\varphi_2 \geq 0$ respectively.

7. We next address the case of $D_0$ which in view of (8.21) can similarly be linked to the case of $D_2$ in a one-to-one way. Moving from the point $(1, 1) \in C$ down to the point $(0, 0) \in D_0$ along the main diagonal in $[0, 1]^2$, we know that there exists the (first) point $(\gamma, \gamma)$ that belongs to $D_0$. Equivalently $\gamma$ can also be formally defined by
\begin{equation}
\gamma = \sup \{ \varphi \in [0, 1] \mid (\varphi, \varphi) \in D_0 \}.
\end{equation}

Clearly the supremum in (8.24) is attained since $D_0$ is closed and we have $\gamma \in (0, 1)$ since $(1, 1) \in C$. Similarly to (8.13) and (8.22) we then define the (least) upper boundary between $C$ and $D_0$ by setting
\begin{equation}
b_0^1(\varphi_1) = \sup \{ \varphi_2 \in [0, 1] \mid (\varphi_1, \varphi_2) \in D_0 \}
\end{equation}
for $\varphi_1 \in [0, \gamma]$, and the (least) lower boundary between $C$ and $D_0$ by setting
\begin{equation}
b_0^2(\varphi_2) = \sup \{ \varphi_1 \in [0, 1] \mid (\varphi_1, \varphi_2) \in D_0 \}
\end{equation}
for $\varphi_2 \in [0, \gamma]$. Clearly the suprema in (8.25) and (8.26) are attained since $D_0$ is closed. In view of (8.20), it is clear that the graphs of $b_0^1$ and $b_0^2$ are mirror images of each other across the main diagonal in $[0, \gamma]^2$, so that $b_0^1 = b_0^2$ on $[0, \gamma]$ and we set
\begin{equation}
b_0(\varphi) := b_0^1(\varphi) = b_0^2(\varphi)
\end{equation}
for $\varphi \in [0, \gamma]$. Similarly to Proposition 8 and Proposition 10 above, we now show that $b_0$ can be used to describe the entire boundary of $D_0$ in $[0, \infty)^2$ (see Figure 1 below).

Proposition 12. The following identity holds
\begin{equation}
D_0 = \{ (\varphi_1, \varphi_2) \in [0, \gamma]^2 \mid \varphi_1 \leq \varphi_2 \leq b_0(\varphi_1) \text{ or } \varphi_2 \leq \varphi_1 \leq b_0(\varphi_2) \}
\end{equation}
with \( b_0(0) = 1/\beta \) and \( b_0(\gamma) = \gamma \in (1/\beta, 1) \). The mapping \( \varphi \mapsto b_0(\varphi) \) is concave and continuous on \([0, \gamma]\).

**Proof.** All claims follow by convexity (and closeness) of \( D_0 \) established in Proposition 7 above combined with the symmetry relations (8.20) and (8.21). The latter symmetry relation links \( D_0 \) to \( D_2 \) in a one-to-one way and this enables us to conclude that \( b_0(0) = 1/\beta \) as claimed. The final claim \( b_0(\gamma) = \gamma \in (1/\beta, 1) \) is evident from (8.24)-(8.26) above. \( \square \)

The one-to-one correspondence between \( D_0 \) and \( D_2 \) obtained by the symmetry relation (8.21) enables us to transfer the facts stated following Proposition 9 above from \( D_2 \) to \( D_0 \). In particular, this yields that the mapping \( \varphi \mapsto b_0(\varphi) \) is (firstly) increasing on \([0, \delta] \) and (then) decreasing on \([\delta, \gamma] \) for some \( \delta \in (0, \gamma) \) (see Figure 1 below).

8. Another consequence of the one-to-one correspondence between \( D_0 \) and \( D_2 \) (and hence \( D_1 \) as well) is the possibility to describe the asymptotic behaviour of \( b_1 \) and \( b_2 \) at infinity.

**Proposition 13.** We have

\[
\lim_{\varphi_1 \to \infty} \frac{b_1(\varphi_1)}{\varphi_1} = \lim_{\varphi_2 \to \infty} \frac{b_2(\varphi_2)}{\varphi_2} = \beta. \tag{8.29}
\]

**Proof.** The first equality follows by the symmetry relation (8.20) implying that \( b_1 \) coincides with \( b_2 \) on \([0, \infty) \) so that it is enough to establish the second equality in (8.29). For this, note that the symmetry relation (8.21) yields

\[
(\varphi_1, b_0(\varphi_1)) \in \partial C \iff \left( \frac{1}{\varphi_1}, \frac{b_0(\varphi_1)}{\varphi_1} \right) \in \partial C \tag{8.30}
\]

for \( \varphi_1 \in [0, \gamma] \). Note also that \( (\varphi_1, b_0(\varphi_1)) \in \partial D_0 \) tends to \((0, 1/\beta)\) and \((1/\varphi_1, b_0(\varphi_1)/\varphi_1) \in \partial D_2 \) tends to \((\infty, \infty)\) as \( \varphi_1 \to 0 \). The fact that the point \((1/\varphi_1, b_0(\varphi_1)/\varphi_1) \) belongs to \( \partial C \cap \partial D_2 \) means that this point can be identified with \((b_2(\varphi_2), \varphi_2) \) for some \( \varphi_2 > 0 \) with \( \varphi_2 \to \infty \) as \( \varphi_1 \to 0 \). This shows that

\[
\frac{b_2(\varphi_2)}{\varphi_2} = \frac{1}{\varphi_1} \frac{b_0(\varphi_1)}{\varphi_1} = \frac{1}{b_0(\varphi_1)} \to \frac{1}{\beta} = \beta \tag{8.31}
\]

as \( \varphi_2 \to \infty \). This establishes (8.29) and the proof is complete. \( \square \)

We will continue our study of the sets \( D_0, D_1, D_2 \) in Section 10 below.

9. Smooth fit

In this section we show that the value function \( \hat{V} \) from (4.18) satisfies the smooth fit condition at the optimal stopping boundaries \( b_0, b_1, b_2 \). A key point in the proof is based upon the fact that the boundary points are *Green regular* for \( D_0, D_1, D_2 \) in the sense that the first entry time \( \tau_{D_i}^{\varphi_1, \varphi_2} \) of \((\varphi_1, \varphi_2) \) into \( D_i \) satisfies

\[
\tau_{D_i}^{\varphi_1, \varphi_2} \to 0 \tag{9.1}
\]
with \( P_0 \)-probability one whenever \((\varphi_1^n, \varphi_2^n)\) from \( C \) tends to \((\varphi_1, \varphi_2)\) at the boundary \( \partial C \cap D_i \) for \( i = 0, 1, 2 \) as \( n \to \infty \). The Green regularity follows from the fact that the boundary points are \textit{probabilistically regular} for \( D_0, D_1, D_2 \) in the sense that \( P_0^{\varphi_1^n, \varphi_2^n}(\tau_{D_i} = 0) = 1 \) for every \((\varphi_1, \varphi_2)\) at the boundary \( \partial C \cap D_i \) for \( i = 0, 1, 2 \) combined with the fact that the process \((\Phi^1, \Phi^2)\) is strong Feller which is evident from (5.8) above (cf. [4, Section 3]). The probabilistic regularity is a consequence of the fact that the sets \( D_i \) are convex (as established in Proposition 7 above) so that in view of (5.8) each boundary point from \( \partial C \cap D_i \) satisfies Zaremba’s cone condition for \( D_i \) with \( i = 0, 1, 2 \) (see e.g. [11, Theorem 3.2, p. 250]). These facts establish (9.1) and we can now state the main result of this section.

**Proposition 14 (Smooth fit).** For the value function \( \hat{V} \) from (4.18) we have

\[
\begin{align*}
\hat{V}_{\varphi_1}(\varphi_1, \varphi_2) &= \hat{M}_{\varphi_1}(\varphi_1, \varphi_2) \\
\hat{V}_{\varphi_2}(\varphi_1, \varphi_2) &= \hat{M}_{\varphi_2}(\varphi_1, \varphi_2)
\end{align*}
\]

for all \((\varphi_1, \varphi_2) \in \partial C \cap D_i \) with \( i = 0, 1, 2 \).

**Proof.** We will establish (9.2) and (9.3) for \( D_2 \) and similar arguments can be used for \( D_0 \) and \( D_1 \). For this, let \( \varphi_1 = b_2(\varphi_2) \) with \( \varphi_2 > 0 \) be given and fixed in the sequel.

1. We show that (9.2) holds. For this, we first note that

\[
\liminf_{h \downarrow 0} \frac{\hat{V}(\varphi_1-h, \varphi_2) - \hat{V}(\varphi_1, \varphi_2)}{-h} \geq \liminf_{h \downarrow 0} \frac{\hat{M}(\varphi_1-h, \varphi_2) - \hat{M}(\varphi_1, \varphi_2)}{-h} = 0
\]

since \( \hat{V}(\varphi_1-h, \varphi_2) \leq \hat{M}(\varphi_1-h, \varphi_2) \) and \( \hat{V}(\varphi_1, \varphi_2) = \hat{M}(\varphi_1, \varphi_2) \) with \( \varphi'_1 \rightarrow \hat{M}(\varphi'_1, \varphi) = c(1+\varphi) \) being constant for \( \varphi'_1 > \varphi_2 \geq 1 \). We next show that

\[
\limsup_{h \downarrow 0} \frac{\hat{V}(\varphi_1-h, \varphi_2) - \hat{V}(\varphi_1, \varphi_2)}{-h} \leq 0.
\]

For this, let \( \tau_{D}^{\varphi_1-h, \varphi_2} \) denote the first entry time of \((\Phi^{\varphi_1-h}, \Phi^{\varphi_2})\) into \( D \) for \( h > 0 \) given and fixed. Since \( \tau_{D}^{\varphi_1-h, \varphi_2} \) is optimal for \( \hat{V}(\varphi_1-h, \varphi_2) \) we find by (5.8) that

\[
\hat{V}(\varphi_1-h, \varphi_2) - \hat{V}(\varphi_1, \varphi_2) \geq E_0 \left[ \int_0^{\tau_{D}^{\varphi_1-h, \varphi_2}} (1+\Phi_t^{\varphi_1-h, \varphi_2}) dt + \hat{M} \left( \Phi_t^{\varphi_1-h, \varphi_2}, \Phi_t^{\varphi_2} (\tau_{D}^{\varphi_1-h, \varphi_2}) \right) \right] - E_0 \left[ \int_0^{\tau_{D}^{\varphi_1-h, \varphi_2}} (1+\Phi_t^{\varphi_1} + \Phi_t^{\varphi_2}) dt + \hat{M} \left( \Phi_t^{\varphi_1}, \Phi_t^{\varphi_2} (\tau_{D}^{\varphi_1-h, \varphi_2}) \right) \right] = E_0 \left[ \int_0^{\tau_{D}^{\varphi_1-h, \varphi_2}} (-h \Phi_t^{\varphi_1}) dt - c h \Phi_t^{\varphi_1} I (\tau_{D}^{\varphi_1-h, \varphi_2} \neq \tau_{D}^{\varphi_2}) \right]
\]

for all \( h \in (0, h_0) \) with some \( h_0 > 0 \) sufficiently small, where in the final equality we use (6.4) combined with the two implications (9.7) below which we motivate and derive first.

Recalling (6.4) and definitions of \( \Delta_0, \Delta_1, \Delta_2 \) stated afterwards, we claim that

\[
(\Phi_t^{\varphi_1-h, \varphi_2}, \Phi_t^{\varphi_2} (\tau_{D}^{\varphi_1-h, \varphi_2})) \in \partial C \cap D_i \implies (\Phi_t^{\varphi_1}, \Phi_t^{\varphi_2} (\tau_{D}^{\varphi_1-h, \varphi_2})) \in \Delta_i
\]
for $h \in (0,h_0)$ with some $h_0 > 0$ sufficiently small and $i = 0,1$.

To show (9.7) for $i = 0$ recall that $c_0$ and $c_1$ are contained in $C$ so that the continuous curve $b_0$ stays away from the straight line $c_0$ in particular. Setting $\tau_h := \tau_0^{1-h,\varphi_2}$ to simplify the notation throughout this shows that there exists $\delta > 0$ sufficiently small such that the right-hand side in (9.7) with $i = 0$ implies that $(\varphi_1-h)\Phi^1_{t \tau_h} \leq 1-\delta$ for $h \in (0,\varphi_1)$. This implies that $\Phi^1_{t \tau_h} \leq (1-\delta)/(\varphi_1-h)$ for all $h \in (0,h_0)$ with $h_0 \in (0,\varphi_1)$ given and fixed. It follows that $\Phi^1_{t \tau_h} = \varphi_1 \Phi^1_{t \tau_h} = (\varphi_1-h)\Phi^1_{t \tau_h} + h \Phi^2_{t \tau_h} \leq 1-\delta + h(1-\delta)/(\varphi_1-h_0) = [(1-\delta)(1+h_0)/(\varphi_1-h_0)] \leq 1$ if we choose $h_0 > 0$ small enough. This shows that (9.7) holds for $i = 0$ as claimed.

To show (9.7) for $i = 1$ set $\tau_h := \tau_0^{1-h,\varphi_2}$ to simplify the notation throughout and note that (8.29) shows that there exists $\delta > 0$ sufficiently small such that the right-hand side in (9.7) with $i = 1$ implies that $(\varphi_1-h)\Phi^1_{t \tau_h} \leq 1-\delta \varphi_2 \Phi^2_{t \tau_h}$ for $h \in (0,\varphi_1)$. This implies that $\Phi^1_{t \tau_h} \leq [(1-\delta)/(\varphi_1-h_0)] \varphi_2 \Phi^2_{t \tau_h}$ for all $h \in (0,h_0)$ with $h_0 \in (0,\varphi_1)$ given and fixed. It follows that $\Phi^1_{t \tau_h} = \varphi_1 \Phi^1_{t \tau_h} = (\varphi_1-h)\Phi^1_{t \tau_h} + h \Phi^2_{t \tau_h} \leq (1-\delta) \varphi_2 \Phi^2_{t \tau_h} + h [(1-\delta)/(\varphi_1-h_0)] \varphi_2 \Phi^2_{t \tau_h} \leq [(1-\delta)(1+h_0)/(\varphi_1-h_0)] \varphi_2 \Phi^2_{t \tau_h}$ if we choose $h_0 > 0$ small enough. This shows that (9.7) holds for $i = 1$ as claimed.

Making now use of (6.4) and (9.7) in the middle term of (9.6) above, upon noting that $\tau_0^{1-h,\varphi_2}$ always equals one among $\tau_0^{1-h,\varphi_2}$, $\tau_0^{1-h,\varphi_2}$, $\tau_0^{1-h,\varphi_2}$, respectively, we see that the final equality in (9.6) holds as claimed. Dividing both sides of (9.6) by $-h$ we obtain

$$
\hat{V}(\varphi_1-h, \varphi_2) - \hat{V}(\varphi_1, \varphi_2) \leq E_0 \left[ \int_0^{\tau_0^{1-h,\varphi_2}} \Phi^1_t dt + c \Phi^1_{\tau_0^{1-h,\varphi_2}} I(\tau_0^{1-h,\varphi_2} = \tau_0^{1-h,\varphi_2}) \right]
$$

for all $h \in (0,h_0)$. Letting $h \downarrow 0$ and using that the right-hand side in (9.8) tends to zero by (9.1) and the continuity of $\hat{V}$ we see that (9.5) holds as claimed. Combining (9.4) and (9.5) with the fact that $M_{\varphi_1}(\varphi_1, \varphi_2) = 0$ we see that (9.2) holds as claimed.

2. We show that (9.3) holds. For this, we first note that

$$
\lim_{h \downarrow 0} \frac{\hat{V}(\varphi_1, \varphi_2-h) - \hat{V}(\varphi_1, \varphi_2)}{-h} \geq \lim_{h \downarrow 0} \frac{\hat{M}(\varphi_1, \varphi_2) - \hat{M}(\varphi_1, \varphi_2)}{-h} = c
$$

$$
\lim_{h \downarrow 0} \frac{\hat{V}(\varphi_1, \varphi_2+h) - \hat{V}(\varphi_1, \varphi_2)}{h} \leq \lim_{h \downarrow 0} \frac{\hat{M}(\varphi_1, \varphi_2+h) - \hat{M}(\varphi_1, \varphi_2)}{h} = c
$$

depending on whether $(\varphi_1, \varphi_2-h)$ or $(\varphi_1, \varphi_2+h)$ belongs to $C$ for $h > 0$ respectively. In (9.8) and (9.9) we use that $\hat{V}(\varphi_1, \varphi_2) \leq \hat{M}(\varphi_1, \varphi_2)$ and $\hat{V}(\varphi_1, \varphi_2) = \hat{M}(\varphi_1, \varphi_2)$ with $\varphi_2 \mapsto \hat{M}(\varphi_1, \varphi_2) = (1+\varphi_2^2)$ being linear for $1 \leq \varphi_2 < \varphi_1$. We next show that

$$
\lim_{h \downarrow 0} \frac{\hat{V}(\varphi_1, \varphi_2-h) - \hat{V}(\varphi_1, \varphi_2)}{-h} \leq c
$$

$$
\lim_{h \downarrow 0} \frac{\hat{V}(\varphi_1, \varphi_2+h) - \hat{V}(\varphi_1, \varphi_2)}{h} \geq c
$$

depending on whether $(\varphi_1, \varphi_2-h)$ or $(\varphi_1, \varphi_2+h)$ belongs to $C$ for $h > 0$ respectively. For this, let $\tau_0^{1,\varphi_2}$ denote the first entry time of $(\Phi^1, \Phi^2)$ into $D$ for $h > 0$ given and fixed. Since $\tau_0^{1,\varphi_2}$ is optimal for $\hat{V}(\varphi_1, \varphi_2) = \hat{M}(\varphi_1, \varphi_2)$ we find by (5.8) that

$$
\hat{V}(\varphi_1, \varphi_2) \geq \hat{M}(\varphi_1, \varphi_2) = \hat{M}(\Phi^1_{\tau_0^{1,\varphi_2}}, \Phi^2_{\tau_0^{1,\varphi_2}})
$$

$$
\int_0^{\tau_0^{1,\varphi_2}} (1+\Phi^1_t+\Phi^2_t) dt + \hat{M}(\Phi^1_{\tau_0^{1,\varphi_2}}, \Phi^2_{\tau_0^{1,\varphi_2}})
$$
for all \( h \in (0, h_0) \) with some \( h_0 > 0 \) sufficiently small, where in the final equality we use (6.4) and (9.7) similarly as in (9.6) above. Dividing both sides of (9.13) by \( \mp h \) we obtain

\[
\frac{\hat{V}(\varphi_1; \varphi_2-h) - \hat{V}(\varphi_1; \varphi_2)}{-h} \leq E_0 \left[ \int_0^{\tau_{\varphi_1}^{\varphi_2-h}} \phi_t^2 \, dt + c \phi_{\tau_{\varphi_1}^{\varphi_2-h}}^2 I(\tau_{\varphi_1}^{\varphi_2-h} \neq \tau_{\varphi_1}^{\varphi_2}) \right]
\]

\[
\frac{\hat{V}(\varphi_1; \varphi_2+h) - \hat{V}(\varphi_1; \varphi_2)}{h} \geq E_0 \left[ \int_0^{\tau_{\varphi_1}^{\varphi_2+h}} \phi_t^2 \, dt + c \phi_{\tau_{\varphi_1}^{\varphi_2+h}}^2 I(\tau_{\varphi_1}^{\varphi_2+h} \neq \tau_{\varphi_1}^{\varphi_2}) \right]
\]

for all \( h \in (0, h_0) \). Letting \( h \downarrow 0 \) and using that the right-hand side in (9.14) and (9.15) tends to \( c \) by (9.1) and the continuity of \( \hat{V} \) we see that (9.11) and (9.12) hold as claimed. Combining (9.9)+(9.10) and (9.11)+(9.12) respectively with the fact that \( \hat{M}_{\varphi_2}(\varphi_1; \varphi_2) = c \) we see that (9.3) holds as claimed. This completes the proof.

**Corollary 15** *(\( C^1 \) regularity).* For the value function \( \hat{V} \) from (4.18) we have

\[
(\varphi_1, \varphi_2) \mapsto \hat{V}_{\varphi_1}(\varphi_1; \varphi_2) \text{ is continuous on } (0, \infty)^2
\]

\[
(\varphi_1, \varphi_2) \mapsto \hat{V}_{\varphi_2}(\varphi_1; \varphi_2) \text{ is continuous on } (0, \infty)^2.
\]

**Proof.** We have established in Proposition 14 that \( \hat{V} \) is differentiable on \((0, \infty)^2\). By (8.4) we know that \( \hat{V} \) is concave on \([0, \infty)^2\). The claims (9.16) and (9.17) then follow from the general fact that concave differentiable functions are continuously differentiable on open sets (see e.g. [2, Theorem 2.2.2]). This completes the proof. \( \square \)

**10. Non-monotonicity of the optimal stopping boundaries**

In this section we show that the optimal stopping boundaries \( b_0, b_1, b_2 \) are non-monotone as functions of their arguments and prove the existence of a ‘belly’ which determines their curvature/shape. In the first part of the proof we introduce the local time of \( \Phi \) on a fictitious curve which enables us to decompose the two-dimensional optimal stopping problem into two one-dimensional optimal stopping problems which can be solved explicitly. In the second part of the proof we follow the general hint from [16, Remark 13] on establishing the absence of jumps of the optimal stopping boundaries and make use of Hopf’s boundary point lemma to derive a contradiction with the directional smooth fit. In view of the symmetry relations (8.20)+(8.21) it is sufficient to focus on the optimal stopping boundary \( b_2 \) and these facts then extend to the optimal stopping boundaries \( b_0 \) and \( b_1 \) as discussed in Section 8 above.

1. To derive that the optimal stopping set \( D_2 \) has a ‘belly’ as displayed on Figure 1 below, we first show that not only the point \((\beta, 0)\) belongs to \( D_2 \) as derived in Section 7 above but also a non-trivial vertical segment above \((\beta, 0)\) is contained in \( D_2 \).
Proposition 16. For the stopping set $D_2$ from (8.10) we have

$$\{ \beta \} \times [0, \varphi_2] \subseteq D_2$$

for some $\varphi_2 > 0$ small enough.

Proof. The idea is to introduce the local time of $\Phi$ on the line

$$\zeta_0 = \{ (\varphi_1, \varphi_2) \in [0, \infty)^2 \mid \varphi_1 = 1 \& \varphi_2 \in [1, \infty) \}$$

and decompose the two-dimensional optimal stopping problem (4.18) into two one-dimensional optimal stopping problems that can be solved explicitly.

For this, set $\varphi_1^* := \beta$ throughout and consider the Lagrange reformulation (6.5) of the optimal stopping problem (4.18) that yields

$$\hat{V}(\varphi_1^*, \varphi_2) - \hat{M}(\varphi_1^*, \varphi_2) = \inf_{\tau} E^0_{\varphi_1^*, \varphi_2} \left[ \int_0^\tau (1 + \Phi_1^1 + \Phi_1^2) \, dt - \frac{c}{2} \left( \ell^0_\tau(\Phi) + \ell^1_\tau(\Phi) + \ell^2_\tau(\Phi) \right) \right]$$

for $\varphi_2 \in [0, \infty)$ where the infimum is taken over all stopping times $\tau$ of $\Phi$. Since the left-hand side of (10.3) is non-positive, it is enough to show that the left-hand side of (10.3) is non-negative for all $\varphi_2 > 0$ sufficiently small. For this, adding and subtracting $\ell^0_\tau(\Phi)$ under the expectation sign in (10.3) and noting that

$$\ell^0(\Phi) + \ell^2(\Phi) = \ell^1(\Phi^1)$$

we find that

$$\inf_{\tau} E^0_{\varphi_1^*, \varphi_2} \left[ \int_0^\tau (1 + \Phi_1^1 + \Phi_1^2) \, dt - \frac{c}{2} \left( \ell^0_\tau(\Phi) + \ell^1_\tau(\Phi) + \ell^2_\tau(\Phi) \right) \right]$$

$$\geq \inf_{\tau} E^0_{\varphi_1^*, \varphi_2} \left[ \int_0^\tau (1 + \Phi_1^1) \, dt - \frac{c}{2} \ell^1_\tau(\Phi) \right]$$

$$+ \inf_{\tau} E^0_{\varphi_1^*, \varphi_2} \left[ \int_0^\tau \Phi_1^2 \, dt + \frac{c}{2} \ell^1_\tau(\Phi) - \frac{c}{2} \left( \ell^1_\tau(\Phi) + \ell^2_\tau(\Phi) \right) \right]$$

$$= \inf_{\tau} E^0_{\varphi_1^*, \varphi_2} \left[ \int_0^\tau (1 + \Phi_1^1) \, dt + c(1 \wedge \varphi_1^*) \right] - c(1 \wedge \varphi_1^*)$$

$$+ \inf_{\tau} E^0_{\varphi_1^*, \varphi_2} \left[ \int_0^\tau \Phi_1^2 \, dt + \hat{M}(\Phi_1^1, \Phi_1^2) \right] - \hat{M}(\varphi_1^*, \varphi_2)$$

$$\geq \inf_{\tau} E^0_{\varphi_1^*, \varphi_2} \left[ \int_0^\tau \Phi_1^2 \, dt + c(1 \wedge \varphi_2^2) \right] - c(1 \wedge \varphi_2)$$

for $\varphi_2 \in [0, 1]$ where in the equality we use the Itô-Tanaka formula (cf. [19, p. 223]) applied to $c(1 \wedge \Phi^1_1)$, and the change-of-variable formula with local time on surfaces [15, Theorem 2.1] applied to $\hat{M}(\Phi_1^1, \Phi_1^2)$ similarly to (6.9) above with

$$\hat{M}(\varphi_1, \varphi_2) := c[(1 \vee \varphi_1) \wedge \varphi_2]$$

for $(\varphi_1, \varphi_2) \in [0, \infty)^2$, both combined with the optional sampling theorem upon using that $\Phi_1^1$ and $\Phi_1^2$ are martingales under $P_0$. In the final inequality of (10.5) we use that $\varphi_1^* = \beta$ is an
optimal stopping point in the one-dimensional optimal stopping problem for \( \Phi^i \) as established in Section 7 above as well as that
\[
\hat{M}(\varphi_1, \varphi_2) = c[(1 \lor \varphi_1^*) \land \varphi_2] = c(\varphi_1^* \land \varphi_2) = c\varphi_2 = c(1 \land \varphi_2)
\]
for \( \varphi_2 \in [0, 1] \) as claimed.

Motivated by the right-hand side in (10.5) above, consider the optimal stopping problem
\[
(10.7) \quad \hat{V}(\varphi) = \inf_{\tau} \mathbb{E}_\varphi^0 \left[ \int_0^\tau \Phi_t \, dt + c(1 \land \Phi_\tau) \right]
\]
for \( \varphi \in [0, \infty) \) with \( \mathbb{P}_\varphi^0(\Phi_0 = \varphi) = 1 \) where the process \( \Phi \) and its infinitesimal generator \( \mathbb{L}_\Phi \) are given by (7.2)+(7.3) and (7.4) above, and the infimum in (10.7) is taken over all stopping times \( \tau \) of \( \Phi \). The optimal stopping problem (10.7) is similar to the optimal stopping problem (7.1) and we can use similar arguments to tackle it. Denoting the loss function in (10.7) by
\[
\hat{M}(\varphi) = c(1 \land \varphi)
\]
for \( \varphi \in [0, \infty) \) it follows that the free-boundary problem now reads
\[
(10.8) \quad \mathbb{L}_\Phi \hat{V}(\varphi) = -\varphi \quad \text{for} \quad \varphi \in (\hat{\varphi}_0^*, \hat{\varphi}_1^*)
\]
\[
(10.9) \quad \hat{V}(\hat{\varphi}_i^*) = \hat{M}(\hat{\varphi}_i^*) \quad \text{for} \quad i = 0, 1 \quad \text{(instantaneous stopping)}
\]
\[
(10.10) \quad \hat{V}'(\hat{\varphi}_i^*) = \hat{M}'(\hat{\varphi}_i^*) \quad \text{for} \quad i = 0, 1 \quad \text{(smooth fit)}
\]
where \( 0 < \hat{\varphi}_0^* < 1 < \hat{\varphi}_1^* < \infty \) are the optimal stopping/boundary points to be found and we have \( \hat{V}(\varphi) = \hat{M}(\varphi) \) for \( \varphi \in [0, \hat{\varphi}_0^*) \cup (\hat{\varphi}_1^*, \infty) \) as well (in addition to (10.9) above).
The general solution to the ordinary differential equation (10.8) is given by

\[(10.11) \hat{V}(\varphi) = \hat{A}\varphi + \hat{B} + \frac{1}{\mu^2} \varphi(1 - \log \varphi)\]

for \(\varphi > 0\) where \(\hat{A}\) and \(\hat{B}\) are two undetermined real constants. Boundary conditions (10.9) and (10.10) then read as follows

\[(10.12) \hat{A}\tilde{\varphi}_0^* + \hat{B} + \frac{1}{\mu^2} \tilde{\varphi}_0^*(1 - \log \tilde{\varphi}_0^*) = c\tilde{\varphi}_0^* \]

\[(10.13) \hat{A}\tilde{\varphi}_1^* + \hat{B} + \frac{1}{\mu^2} \tilde{\varphi}_1^*(1 - \log \tilde{\varphi}_1^*) = c\]

\[(10.14) \hat{A} - \frac{1}{\mu^2} \log \tilde{\varphi}_0^* = c\]

\[(10.15) \hat{A} - \frac{1}{\mu^2} \log \tilde{\varphi}_1^* = 0.\]

It is a matter of routine to verify that the unique solution to (10.12)-(10.15) is given by

\[(10.16) \tilde{\varphi}_0^* = \frac{c\mu^2}{e^{c\mu^2} - 1} \quad \& \quad \tilde{\varphi}_1^* = \frac{c\mu^2e^{c\mu^2}}{e^{c\mu^2} - 1} \]

\[(10.17) \hat{A}^* = c + \frac{1}{\mu^2} \log \tilde{\varphi}_0^* \quad \& \quad \hat{B}^* = -\frac{1}{\mu^2} \tilde{\varphi}_0^*.\]

Note that \(\tilde{\varphi}_0^* \in (0, 1)\) and \(\tilde{\varphi}_1^* \in (1, \infty)\) as needed. Inserting \(\hat{A}^*\) and \(\hat{B}^*\) from (10.17) to (10.11) we obtain a candidate value function \(\hat{V}^*\) for the optimal stopping problem (10.7). Applying the Itô-Tanaka formula (cf. [19, p. 223]) to \(\hat{V}^*\) composed with \(\Phi\), which reduces to Itô’s formula due to smooth fit (10.10), and making use of the optional sampling theorem, it is easily verified that \(\hat{V}^*\) coincides with the value function \(\hat{V}\) from (10.7) and the optimal stopping time (at which the infimum in (10.7) is attained) is given by

\[(10.18) \tau^* = \inf \{ t \geq 0 \mid \Phi_t \notin (\tilde{\varphi}_0^*, \tilde{\varphi}_1^*) \}\]

where \(\tilde{\varphi}_0^*\) and \(\tilde{\varphi}_1^*\) are given by (10.16) above. This in particular shows that the interval \([0, \tilde{\varphi}_0^*]\) is contained in the stopping set of the optimal stopping problem (10.7). Translating this conclusion to the right-hand side of (10.5) above we see that its value equals zero whenever \(\varphi_2\) belongs to \([0, \tilde{\varphi}_0^*]\). It follows therefore from (10.3) and (10.5) that \(\varphi_2\) in (10.1) can be taken to be equal to \(\tilde{\varphi}_0^* = c\mu^2/(e^{c\mu^2} - 1)\) and the proof is complete. \(\square\)

2. We now show that the ‘belly’ of the optimal stopping set \(D_2\) is not flat but curved (see Figure 1 above). For this, suppose that this is not the case. Then \([a, b] \times [c, d] \subseteq C\) with \(\{b\} \times [c, d] \subseteq D_2\) and \(\{b\} \times [d, b] \subseteq C\) for some \(a < b\) with \([a, b] \subseteq [1, \beta]\) and some \(c < d\) with \([c, d] \subseteq [0, a]\). The initial claim is then a direct consequence of the following fact.

**Proposition 17.** If the ‘belly’ of the optimal stopping set \(D_2\) would be flat as described above, then the horizontal smooth fit condition (9.2) would fail on \(\{b\} \times [c, d] \subseteq \partial C \cap D_2\).
Proof. Suppose that the ‘belly’ of the optimal stopping set \( D_2 \) is flat as described above. Set \( R^0 = (a, b) \times (c, d) \) and \( R^1 = (a, b) \times (c, d) \) with \( R = [a, b] \times [c, d] \). Recalling the Lagrange reformulation (6.5) of the optimal stopping problem (4.18), and arguing as in the proof of Theorem 12 in [16], we find that the value function \( \hat{V} \) from (4.18) solves the equation

\[
\Box \phi \hat{V} = -\hat{H}
\]

on \( R^0 \) and belongs to \( C^4(R^1) \) where \( \Box \phi \) is given by (5.9) above and we set

\[
\hat{H} (\varphi_1, \varphi_2) = 1 + \varphi_1 + \varphi_2
\]

for \((\varphi_1, \varphi_2) \in [0, \infty)^2\). Differentiating both sides of (10.19) with respect to \( \varphi_2 \) and defining the differential operator \( \tilde{\Box} \) by setting

\[
\tilde{\Box} = \varphi_1^2 \Box_{\varphi_1 \varphi_1} + \varphi_1 \varphi_2 \Box_{\varphi_1 \varphi_2} + \varphi_2^2 \Box_{\varphi_2 \varphi_2} + 2 \varphi_1 \partial_{\varphi_1} + 4 \varphi_2 \partial_{\varphi_2} + 2
\]

we find that \( \hat{V}_{\varphi_2} \) solves the equation

\[
\tilde{\Box} \hat{V}_{\varphi_2} = 0
\]

on \( R^0 \). We will now complete the proof in two steps as follows.

1. We claim that the strict inequality holds

\[
\hat{V}_{\varphi_2} (\varphi_1, \varphi_2) < 0
\]

for all \((\varphi_1, \varphi_2) \in R^0\). For this, suppose that (10.23) fails for some \((\varphi_1, \varphi_2) \in R^0\). Recalling that \( \{b\} \times (d, b] \subseteq C \), consider the ball \( b(z, r) \) with centre at \( z := (b, d) \) and radius \( r > 0 \) small enough so that \( b(z, r) \subseteq \Delta_2 \), where \( \Delta_2 \) is defined following (6.4) above. Enlarge \( R^0 \) by setting \( \tilde{R}^0 := R^0 \cup (b(z, r) \cap C) \) and note that the same arguments as above show that the equations (10.19) and (10.22) hold on \( \tilde{R}^0 \) too. Since the coefficients of \( \tilde{\Box} \) are continuous and the set \( \tilde{R}^0 \) is bounded we can conclude that \( \tilde{\Box} \) is uniformly elliptic on \( \tilde{R}^0 \) (cf. [9, p. 31]). The hypothesis that (10.23) fails for some \((\varphi_1, \varphi_2) \in R^0\), combined with the fact that \( \hat{V}_{\varphi_2} \leq 0 \) on \( \tilde{R}^0 \) by (8.4) above, implies that \( \hat{V}_{\varphi_2} (\varphi_1, \varphi_2) = 0 \) so that \( \hat{V}_{\varphi_2} \) attains its maximum in the interior of \( \tilde{R}^0 \) (i.e. not at its boundary alone). Hence by the strong maximum principle for elliptic equations (see Theorem 3.5 in [9, p. 35] and the second sentence following its proof) we can conclude that \( \hat{V}_{\varphi_2} = 0 \) on the entire \( \tilde{R}^0 \). This in particular means that \( \varphi_2 \mapsto \hat{V} (b, \varphi_2) \) is linear on \([d, d + r]\). Since \( \varphi_2 \mapsto \hat{V} (b, \varphi_2) = c(1 + \varphi_2) \) is linear on \([c, d]\) as well, and the vertical smooth fit (9.3) holds at \( z = (b, d) \), it follows that \( \hat{V}(b, \varphi_2) = c(1 + \varphi_2) \) for all \( \varphi_2 \in [c, d + r] \) so that \( \{b\} \times (d, d + r] \subseteq D \) which is a contradiction. This establishes that (10.23) is satisfied as claimed.

2. Fix any point \( e \) in \((c, d)\) and note that \( \hat{V}_{\varphi_2} (b, e) = 0 \) since \( \hat{V} \in C^4(R^1) \subseteq C^2(R^1) \) and \( \hat{V} (b, \varphi_2) = c(1 + \varphi_2) \) for \( \varphi_2 \in [c, d] \). Hence we see that (10.23) reads as \( \hat{V}_{\varphi_2} (\varphi_1, \varphi_2) < \hat{V}_{\varphi_2} (b, e) \) for all \((\varphi_1, \varphi_2) \in R^0\). Moreover, we know that \( \tilde{\Box} \) is uniformly elliptic and \( \tilde{\Box} \hat{V}_{\varphi_2} \geq 0 \) holds on \( R^0 \) by (10.22) above. Finally, it is evident that \( R^0 \) satisfies an interior sphere condition at \( z := (b, e) \in \partial R^0 \) (i.e. there exist \( w \in R^0 \) and \( r > 0 \) such that \( b(w, r) \subseteq R^0 \) and \( z \in \partial(b(w, r)) \)). These facts show that Hopf’s boundary point lemma for
elliptic equations (see [9, Lemma 3.4 p. 34]) is applicable and thus the outer normal derivative of \( V_{\varphi_2\varphi_2} \) at \( z = (b, e) \) must be strictly positive. In other words, we have

\[
(10.24) \quad \left(V_{\varphi_2\varphi_2}\right)_{\varphi_1}(b, e) > 0.
\]

This conclusion shows that the horizontal smooth fit condition (9.2) cannot hold on \( \{b\} \times [c, d] \) as claimed, since otherwise we would have \( (V_{\varphi_2\varphi_2})_{\varphi_1}(b, e) = (V_{\varphi_1})_{\varphi_2\varphi_2}(b, e) = 0 \) due to \( V \in C^4(R^1) \subseteq C^3(R^1) \), and the proof is complete. \( \square \)

11. Free-boundary problem

In this section we derive a free-boundary problem that stands in one-to-one correspondence with the optimal stopping problem (4.18) and establish the fact that the value function \( \hat{V} \) and the optimal stopping boundary \( \partial C \) solve the free-boundary problem uniquely. These considerations will be continued in the next section.

1. Consider the optimal stopping problem (4.18) where the strong Markov/Feller process \( \Phi = (\Phi^1, \Phi^2) \) solves the system of stochastic differential equations (5.6)+(5.7). Recalling that the infinitesimal generator \( \mathbb{L}_\Phi \) of \( \Phi \) is given by (5.9) above, and relying on other properties of \( \hat{V} \) and \( \partial C \) derived in Section 8 above, we are naturally led to formulate the following free-boundary problem for finding \( \hat{V} \) and \( \partial C \):

\[
(11.1) \quad \mathbb{L}_\Phi \hat{V} = -\hat{H} \text{ on } C \\
(11.2) \quad \hat{V} = \hat{M} \text{ on } D \quad \text{(instantaneous stopping)} \\
(11.3) \quad \hat{V}_{\varphi_i} = \hat{M}_{\varphi_i} \text{ on } \partial C \text{ for } i = 1, 2 \quad \text{(smooth fit)}
\]

where \( \hat{H} \) is given by (10.20) above and \( \hat{M} \) is given by (4.13) above. The continuation set \( C \) and the stopping set \( D \) are formally defined by (8.1) and (8.2) respectively. We know from the results of Section 8 that the optimal stopping boundary \( \partial C \) can be fully described by means of the functions \( b_0 \) and \( b_1 \) defined in Section 8 above via the equivalence \( (\varphi_1, \varphi_2) \in \partial C \) if and only if either \( (\varphi_1, \varphi_2) \in \partial C \cap D_0 \) and \( \varphi_i = b_0(\varphi_j) \) when \( \varphi_i \geq \varphi_j \) for \( i \neq j \in \{1, 2\} \) or \( (\varphi_1, \varphi_2) \in \partial C \cap D_i \) and \( \varphi_j = b_i(\varphi_i) \) for \( i \neq j \in \{1, 2\} \) where \( D_0, D_1, D_2 \) are given by (8.8)-(8.10) above (see Figure 1 above). Clearly the global condition (11.2) can be replaced by the local condition \( \hat{V} = \hat{M} \) on \( \partial C \) so that the free-boundary problem (11.1)-(11.3) needs to be considered on the closure of \( C \) only (extending \( \hat{V} \) to the rest of \( D \) as \( \hat{M} \)).

2. To formulate the existence and uniqueness result for the free-boundary problem (11.1)-(11.3) we let \( C \) denote the class of functions \( (F; a_0, a_1) \) such that

\[
(11.4) \quad F \text{ is concave and continuous on } [0, \infty)^2 \text{ and belongs to } C^4(0,\infty)^2 \cap C^2(C_{a_0, a_1}) \\
(11.5) \quad a_0 \text{ is concave and continuous on } [0, \delta] \text{ with } a_0(0) = 1/\beta \text{ and } a_0(\delta) = \delta \text{ and } \varphi < a_0(\varphi) < 1 \text{ for } \varphi \in (0, \delta) \text{ with some } \delta \in (0, 1) \\
(11.6) \quad a_1 \text{ is convex and continuous on } [0, \infty) \text{ with } a_1(0) = \beta \text{ and } a_1(\infty) = \infty \text{ and } a_1(\varphi) > 1 \lor \varphi \text{ for } \varphi \in [0, \infty)
\]

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where \( C_{a_0,a_1} := \{ (\varphi_1, \varphi_2) \in [0,\infty)^2 \mid a_0(\varphi_i) < \varphi_j < a_1(\varphi_i) \text{ when } \varphi_i \leq \varphi_j \text{ and } \varphi_i \in [0,\delta] \text{ or } \varphi_i \leq \varphi_j < a_1(\varphi_i) \text{ when } \varphi_i \leq \varphi_j \text{ and } \varphi_i \in (\delta,\infty) \text{ for } i \neq j \in \{1,2\} \text{ and some } \delta \in (0,1) \} \) is the open set surrounded by \( a_0 \) and \( a_1 \) (applied twice).

**Theorem 18.** The free-boundary problem (11.1)-(11.3) has a unique solution \((\hat{V}; b_0, b_1)\) in the class \( \mathcal{C} \) where \( \hat{V} \) is given by (4.18) while \( b_0 \) and \( b_1 \) are defined in Section 8 above.

**Proof.** Combining the results of Proposition 5 and Corollary 15 with the arguments leading to (10.19) above, we see that the value function \( \hat{V} \) from (4.18) satisfies (11.4) and solves the boundary value problem (11.1)-(11.3) with \( \partial \mathcal{C} \) described by \( b_0 \) and \( b_1 \) from Section 8 as recalled above. Moreover, combining the results of Propositions 8-12 we see that \( b_0 \) and \( b_1 \) satisfy (11.5) and (11.6) respectively. This shows that \((\hat{V}; b_0, b_1)\) solves the free-boundary problem (11.1)-(11.3) in the class \( \mathcal{C} \) as claimed. To derive uniqueness of the solution we will first see in the next section that any solution \((F; a_0, a_1)\) to the free-boundary problem (11.1)-(11.3) in the class \( \mathcal{C} \) admits a closed triple-integral representation of \( F \) expressed in terms of \( a_0 \) and \( a_1 \), which in turn solve a coupled system of nonlinear Fredholm integral equations, and we will see that this system cannot have other solutions satisfying the specified properties. Drawing these facts together we can conclude that there cannot exist more than one solution to the free-boundary problem (11.1)-(11.3) in the class \( \mathcal{C} \) as claimed. \( \square \)

### 12. Nonlinear integral equations

In this section we show that the optimal stopping boundaries \( b_0 \) and \( b_1 \) can be characterised as the unique solution to a coupled system of nonlinear Fredholm integral equations (recall that \( b_2 \) coincides with \( b_1 \) in terms of its functional rule). This also yields a closed triple-integral representation of the value function \( \hat{V} \) expressed in terms of the optimal stopping boundaries \( b_0 \) and \( b_1 \). As a consequence of the existence and uniqueness result for the coupled system of nonlinear Fredholm integral equations we also obtain uniqueness of the solution to the free-boundary problem (11.1)-(11.3) as explained in the proof of Theorem 18 above. Finally, collecting the results derived throughout the paper we conclude our exposition at the end of this section by disclosing the solution to the initial problem.

1. To formulate the theorem below, let \( p \) denote the transition probability density function of the (time-homogeneous) Markov process \( \Phi = (\Phi^1, \Phi^2) \) under \( P_0 \) in the sense that

\[
(12.1) \quad P_{\varphi_1,\varphi_2}^t (\Phi^1_t \leq \psi_1, \Phi^2_t \leq \psi_2) = \int_0^{\psi_1} \int_0^{\psi_2} p(t; \varphi_1, \varphi_2; \eta_1, \eta_2) d\eta_1 d\eta_2
\]

for \( t > 0 \) with \((\varphi_1, \varphi_2)\) and \((\psi_1, \psi_2)\) in \([0,\infty)^2\). A lengthy but straightforward calculation based on (5.8) shows that

\[
(12.2) \quad p(t; \varphi_1, \varphi_2; \psi_1, \psi_2) = \frac{1}{2\pi \sqrt{3} \mu^2 t \psi_1 \psi_2} \exp \left[ - \frac{1}{3} \left( \mu^2 t + \log \left( \frac{\psi_1 \psi_2}{\varphi_1 \varphi_2} \right) \right) + \frac{1}{\mu^2 t} \left[ \log^2 \left( \frac{\psi_1 \varphi_2}{\psi_2 \varphi_1} \right) + \log \left( \frac{\psi_1}{\varphi_1} \right) \log \left( \frac{\psi_2}{\varphi_2} \right) \right] \right]
\]

for \( t > 0 \) with \((\varphi_1, \varphi_2)\) and \((\psi_1, \psi_2)\) in \([0,\infty)^2\). Recalling from Section 8 above that the functions \( b_0 \) and \( b_1 \) are sufficient to describe the entire boundary of the continuation set, we
can then evaluate the expression of interest in the theorem below as follows

\begin{equation}
E_{\varphi_1, \varphi_2}^{0} \left[ \int_{0}^{\infty} \hat{H}(\Phi^1_s, \Phi^2_s) I((\Phi^1_s, \Phi^2_s) \in C) \, ds \right] \\
= \int_{0}^{\infty} \left( \int_{0}^{\infty} \int_{b_0(\psi) \cup \psi_1}^{b_1(\psi_1)} \hat{H}(\psi_1, \psi_2) p(s; \varphi_1, \varphi_2; \psi_1, \psi_2) \, ds \right) \, ds \\
= \int_{0}^{\infty} \left( \int_{0}^{\infty} \int_{b_0(\psi) \cup \psi_1}^{b_1(\psi_1)} \hat{H}(\psi_1, \psi_2) p(s; \varphi_1, \varphi_2; \psi_1, \psi_2) \, ds \right) \, ds \\
= 2 \int_{0}^{\infty} \int_{0}^{\infty} \int_{b_0(\psi) \cup \psi_1}^{b_1(\psi_1)} \hat{H}(\psi_1, \psi_2) p(s; \varphi_1, \varphi_2; \psi_1, \psi_2) \, ds \, ds \, ds
\end{equation}

for \((\varphi_1, \varphi_2) \in [0, \infty)^2\) where the final equality follows by symmetry relative to the main diagonal in \([0, \infty)^2\) and we recall that \(\hat{H}\) is defined in (10.20) above.

**Theorem 19 (Existence and uniqueness).** The optimal stopping boundaries \(b_0\) and \(b_1\) in the problem (4.18) can be characterised as the unique solution to the coupled system of nonlinear Fredholm integral equations

\begin{align}
\varphi_1 + b_0(\varphi_1) &= \frac{2}{c} \int_{0}^{\infty} \int_{0}^{\infty} \int_{b_0(\psi) \cup \psi_1}^{b_1(\psi_1)} \hat{H}(\psi_1, \psi_2) p(s; \varphi_1, \varphi_2; \psi_1, \psi_2) \, ds \, ds \, ds \\
1 + \varphi_1 &= \frac{2}{c} \int_{0}^{\infty} \int_{0}^{\infty} \int_{b_0(\psi) \cup \psi_1}^{b_1(\psi_1)} \hat{H}(\psi_1, \psi_2) p(s; \varphi_1, \varphi_2; \psi_1, \psi_2) \, ds \, ds \, ds
\end{align}

in the class of functions \(a_0\) and \(a_1\) satisfying (11.5) and (11.6) respectively, where \(\varphi_1\) in (12.4) belongs to \([0, \gamma]\) with \(b_0(\gamma) = \gamma\) for some \(\gamma \in (0, 1)\) and \(\varphi_1\) in (12.5) belongs to \([0, \infty)\). The value function \(\hat{V}\) in the problem (4.18) admits the following representation

\begin{equation}
\hat{V}(\varphi_1, \varphi_2) = 2 \int_{0}^{\infty} \int_{0}^{\infty} \int_{b_0(\psi) \cup \psi_1}^{b_1(\psi_1)} \hat{H}(\psi_1, \psi_2) p(s; \varphi_1, \varphi_2; \psi_1, \psi_2) \, ds \, ds \, ds
\end{equation}

for \((\varphi_1, \varphi_2) \in [0, \infty)^2\). The optimal stopping time in the problem (4.18) is given by

\begin{equation}
\tau_{b_0, b_1} = \inf \{ t \geq 0 \mid \Phi^i_t \geq \Phi^j_t \text{ with } \Phi^i_t \leq b_0(\Phi^j_t) \text{ or } \Phi^i_t \geq b_1(\Phi^j_t) \text{ for } i \neq j \text{ in } \{1, 2\} \}
\end{equation}

under \(P_{0, \varphi_1, \varphi_2}^{0}\) with \((\varphi_1, \varphi_2) \in [0, \infty)^2\) given and fixed (see Figure 1 above).

**Proof.** (1) Existence. We first show that the value function \(\hat{V}\) in the problem (4.18) admits the representation (12.6) and that the optimal stopping boundaries \(b_0\) and \(b_1\) solve the system (12.4)+(12.5). Recalling that \(b_0\) and \(b_1\) satisfy the properties (11.5) and (11.6) this will establish the existence of a solution to the system (12.4)+(12.5).

For this, recall that by (8.4) in Proposition 5 we know that \(\hat{V}\) is concave and from Corollary 15 we know that \(\hat{V}\) is globally \(C^1\) on \((0, \infty)^2\). These properties however are generally insufficient to apply a known extension of Itô’s formula to \(\hat{V}(\Phi^1, \Phi^2)\) due to not knowing the size of the second partial derivatives \(\hat{V}_{\varphi_1, \varphi_1}, \hat{V}_{\varphi_1, \varphi_2}, \hat{V}_{\varphi_2, \varphi_2}\) close to the optimal stopping boundaries. Note that we know that the optimal stopping boundaries are convex/concave, however, this
is generally insufficient to derive a local boundedness of the second partial derivatives close to the optimal stopping boundaries (without having their smoothness) using the general theory of elliptic PDEs (see [9]). A semimartingale decomposition of \( \hat{V}(\varphi^1, \varphi^2) \) obtained by Itô’s formula is useful because it leads to Dynkin’s formula (upon localising, taking expectations, and passing to the limit) which in turn yields the representation (12.6). We will show in the proof below that Dynkin’s formula can be derived without appealing to Itô’s formula and/or without formally verifying that the second partial derivatives are locally bounded close to the optimal stopping boundaries. This will be accomplished in several steps below by exploiting the underlying convexity/concavity in the problem (4.18) combined with the fact that the expectation of the running local time of \((\varphi^1, \varphi^2)\) on the (approximating) optimal stopping boundaries remains uniformly bounded as the time tends to infinity (recall that \((\varphi^1, \varphi^2)\) itself converges to zero so that this is rather intuitive).

1. We begin by localising the process \( \Phi = (\varphi^1, \varphi^2) \). For this, let \( N \geq 1 \) be given and fixed (large) and consider the first exit time of \( \Phi \) from the square \([1/N, N]^2\) given by

\[
(12.8) \quad \rho_N = \inf \{ t \geq 0 \mid \Phi_t \notin [1/N, N]^2 \}.
\]

Let \( \Phi^{\rho_N} = (\Phi_{t \wedge \rho_N})_{t \geq 0} \) denote the process \( \Phi \) stopped at \( \rho_N \). Clearly the process \( \Phi^{\rho_N} \) stays in the square \([1/N, N]^2\) all the time while both \( \hat{V} \) and \( \hat{V}_{\varphi_i} \) are continuous and thus bounded on \([1/N, N]^2\) for \( i = 1, 2 \). As we have not established that \( \hat{V}_{\varphi_1, \varphi_2}, \hat{V}_{\varphi_1, \varphi_2}, \hat{V}_{\varphi_2, \varphi_2} \) are locally bounded close to the optimal stopping boundaries, we proceed by modifying the value function \( \hat{V} \) within the continuation set \( C \) close to its boundary.

2. For \( n \geq 1 \) given and fixed (large) define the sets \( C_n := \{(\varphi_1, \varphi_2) \in [0, \infty)^2 \mid \hat{V}(\varphi_1, \varphi_2) < \hat{M}(\varphi_1, \varphi_2) - 1/n \} \) and \( D_n := \{(\varphi_1, \varphi_2) \in [0, \infty)^2 \mid \hat{V}(\varphi_1, \varphi_2) \geq \hat{M}(\varphi_1, \varphi_2) - 1/n \} \). Set \( C_n^i := C_n \cap \Delta_i \) and \( D_n^i := D_n \cap \Delta_i \) where \( \Delta_i \) are defined following (6.4) above for \( i = 0, 1, 2 \). Clearly \( D_n^i \downarrow D_i \) as \( n \to \infty \) for \( i = 0, 1, 2 \). Using the same arguments as in the proof of Proposition 7 above we find that each set \( D_n^i \) is convex for \( i = 0, 1, 2 \). Hence we can conclude that the boundary \( b_n^i \) of \( D_n^i \) restricted to the square \([1/N, N]^2\) converges uniformly to the boundary \( b_i \) restricted to the square \([1/N, N]^2\) as \( n \to \infty \) for \( i = 0, 1, 2 \). Thus, as in the case of the sets \( D_0, D_1, D_2 \) and their boundaries \( b_0, b_1, b_2 \), the boundary of the set \( D_0^i \) restricted to the square \([1/N, N]^2\) is described by a concave/continuous function \( b_n^i : [1/n, \gamma_n] \to [0, 1] \) and the boundaries of the sets \( D_1^i \) and \( D_2^i \) are described by a convex/continuous function \( b_n^i : [1/N, N] \to [1, N] \) for all \( n \geq n_0 \) with \( n_0 \geq 1 \) sufficiently large.

3. We approximate the value function \( \hat{V} \) by functions \( \hat{V}^n \) defined as follows

\[
(12.9) \quad \hat{V}^n(\varphi_1, \varphi_2) = \hat{V}(\varphi_1, \varphi_2) \text{ if } (\varphi_1, \varphi_2) \in C_n
\]

\[
= \hat{M}(\varphi_1, \varphi_2) - \frac{1}{n} \text{ if } (\varphi_1, \varphi_2) \in D_n
\]

for \((\varphi_1, \varphi_2) \in [0, \infty)^2\) with \( n \geq n_0 \) given and fixed. Clearly \( \hat{V}^n \) is a continuous function on \([0, \infty)^2\) and moreover \( \hat{V}^n \) restricted to \( C_n \) and \( D_n \) belongs to \( C^2(\bar{C}_n) \) and \( C^2(\bar{D}_n) \) respectively. Thus the change-of-variable formula with local time on surfaces [15, Theorem 2.1] is applicable to \( \hat{V}^n \) composed with \( \Phi^{\rho_N} = (\Phi_{t \wedge \rho_N}, \Phi_{t \wedge \rho_N}) \) and this gives

\[
(12.10) \quad \hat{V}^n(\Phi_{t \wedge \rho_N}) = \hat{V}^n(\varphi) + \int_0^t \hat{V}^n_{\varphi_1}(\Phi_{s \wedge \rho_N}) d\Phi_{t \wedge \rho_N}^{1,n} + \int_0^t \hat{V}^n_{\varphi_2}(\Phi_{s \wedge \rho_N}) d\Phi_{t \wedge \rho_N}^{2,n} + \int_0^t \mathbb{I}_{\Phi_{s \wedge \rho_N}} \hat{V}^n(\Phi_{s \wedge \rho_N}) \, ds
\]
\[ + \frac{1}{2} \int_0^t \left[ \hat{V}_{\varphi_2}(\Phi_{s}^{1, \rho N}, b_0^n(\Phi_{s}^{1, \rho N}) +) - \hat{V}_{\varphi_2}(\Phi_{s}^{1, \rho N}, b_0^n(\Phi_{s}^{1, \rho N}) -) \right] d\ell_s^{b_0^n}(\Phi^{\rho N}) \\
+ \frac{1}{2} \int_0^t \left[ \hat{V}_{\varphi_1}(b_0^n(\Phi_{s}^{2, \rho N}) +, \Phi_{s}^{2, \rho N}) - \hat{V}_{\varphi_1}(b_0^n(\Phi_{s}^{2, \rho N}) -, \Phi_{s}^{2, \rho N}) \right] d\ell_s^{b_0^n}(\Phi^{\rho N}) \\
+ \frac{1}{2} \int_0^t \left[ \hat{V}_{\varphi_2}(\Phi_{s}^{1, \rho N}, b_1^n(\Phi_{s}^{1, \rho N}) +) - \hat{V}_{\varphi_2}(\Phi_{s}^{1, \rho N}, b_1^n(\Phi_{s}^{1, \rho N}) -) \right] d\ell_s^{b_1^n}(\Phi^{\rho N}) \\
+ \frac{1}{2} \int_0^t \left[ \hat{V}_{\varphi_1}(b_1^n(\Phi_{s}^{2, \rho N}) +, \Phi_{s}^{2, \rho N}) - \hat{V}_{\varphi_1}(b_1^n(\Phi_{s}^{2, \rho N}) -, \Phi_{s}^{2, \rho N}) \right] d\ell_s^{b_1^n}(\Phi^{\rho N}) \\
= \hat{V}(\varphi) + M_t - \int_0^t \hat{H}(\Phi_s) I(\Phi_s \in \mathcal{C}_n) \, ds + \frac{1}{2} L_t^{1, N,N} \]

for \( \varphi \in [0, \infty)^2 \) using (11.1) and (11.2) where \( M_t \) is a continuous martingale (the sum of the first two integrals in the first identity of (12.10) above) and \( L_t^{1, N,N} \) is the sum of the final four integrals in the first identity of (12.10) above. Note that the first partial derivatives \( \hat{V}_{\varphi_1} \) and \( \hat{V}_{\varphi_2} \) are discontinuous over the boundary curves \( b_0^n \) and \( b_1^n \) because these boundary curves are not optimal. However, since \( \hat{V} \) is globally \( C^1 \) on \((0, \infty)^2\) by Corollary 15, it follows that

\begin{align}
\sup_{1/N \leq \varphi_1 \leq N} \left| \hat{V}_{\varphi_1}(\varphi_1, b_0^n(\varphi_1)) - \hat{M}_{\varphi_1}(\varphi_1, b_0^n(\varphi_1)) \right| & \to 0 \\
\sup_{1/N \leq \varphi_1 \leq N} \left| \hat{V}_{\varphi_1}(\varphi_2, b_1^n(\varphi_2)) - \hat{M}_{\varphi_1}(\varphi_2, b_1^n(\varphi_2)) \right| & \to 0
\end{align}

for \( i = 0, 1 \) as \( n \to \infty \). Note that the suprema in (12.11) and (12.12) for \( i = 0, 1 \) provide uniform upper bounds on the modulus of the integrands in the four integrals of (12.10) with respect to the local times. To obtain a control over the local times themselves in these four integrals (their integrators) we now show that their expectations remain uniformly bounded as the running time tends to infinity.

4. We first consider the case of \( b_0^{1,n} \) and \( b_0^{2,n} \) recalling that the two functions coincide by symmetry for \( n \geq 1 \) given and fixed. We thus focus on \( b_0^{1,n} \) in the sequel. Since \( b_0^{1,n} \) is concave we see that \( \Phi_{s}^{2, \rho N} - b_0^{1,n}(\Phi_{s}^{1, \rho N}) \) is a continuous semimartingale so that by the Itô-Tanaka formula we find that

\begin{align}
(\Phi_{s}^{2, \rho N} - b_0^{1,n}(\Phi_{s}^{1, \rho N}))^+ &= (\varphi_2 - b_0^{1,n}(\varphi_1))^+ \\
+ \int_0^t I(\Phi_{s}^{2, \rho N} > b_0^{1,n}(\Phi_{s}^{1, \rho N})) d(\Phi_{s}^{2, \rho N} - b_0^{1,n}(\Phi_{s}^{1, \rho N})) d\Phi_{s}^{1, \rho N} + \frac{1}{2} \ell_{t}^{b_0^{1,n}}(\Phi^{\rho N}) \\
&= (\varphi_2 - b_0^{1,n}(\varphi_1))^+ + \int_0^t I(\Phi_{s}^{2, \rho N} > b_0^{1,n}(\Phi_{s}^{1, \rho N})) d\Phi_{s}^{2, \rho N} \\
&\quad - \int_0^t I(\Phi_{s}^{2, \rho N} > b_0^{1,n}(\Phi_{s}^{1, \rho N})) (b_0^{1,n})(\Phi_{s}^{1, \rho N}) d\Phi_{s}^{1, \rho N} \\
&\quad - \frac{1}{2} \int_0^t I(\Phi_{s}^{2, \rho N} > b_0^{1,n}(\Phi_{s}^{1, \rho N})) \int_0^\infty d\psi_s(b_0^{1,n})(\psi_1) d\psi_s(\Phi^{1, \rho N}) + \frac{1}{2} \ell_{t}^{b_0^{1,n}}(\Phi^{\rho N})
\end{align}

for \( t \geq 0 \) where \((b_0^{1,n})'\) denotes the first derivative of \( b_0^{1,n} \) (its existence follows by the implicit function theorem since smooth fit fails at \( b_0^{1,n} \) as pointed out above). Since \( b_0^{1,n} \) is concave
we see that \( d(b_0^n)' \) defines a non-positive measure on \([1/N, \gamma_n]\) so that the final integral in (12.13) is non-positive. Using this fact in (12.13) we obtain the following pathwise bound on the size of the local time

\[
(12.14) \quad \ell_t^{\Phi}(\Phi^{\rho,N}) \leq 2(\Phi_t^{2,\rho,N} - b_0^{1,n}(\Phi_t^{1,\rho,N}))^+ - M_t
\]

where \( M_t \) is a continuous martingale (the difference between the second and the third integral in (12.13) above) for \( t \geq 0 \). Taking \( E^0_{\varphi_1, \varphi_2} \) on both sides of (12.14) above and using that \( \Phi_t^{2,\rho,N} \leq N \) for all \( t \geq 0 \) we find that

\[
(12.15) \quad E^0_{\varphi_1, \varphi_2}[\ell_t^{b_0^n}] \leq 2N
\]

for all \( t \geq 0 \) and all \( n \geq n_0 \) with \((\varphi_1, \varphi_2) \in [0, \infty)^2\) and \( i = 1, 2 \) (where the case \( i = 2 \) follows from the case \( i = 1 \) by symmetry).

5. We next consider the case of \( b_1^n \) and \( b_2^n \) recalling that the two functions coincide by symmetry for \( n \geq 1 \) given and fixed. We thus focus on \( b_1^n \) in the sequel. Similarly, since \( b_1^n \) is convex we see that \( b_1^n(\Phi^{1,\rho,N}) - \Phi^{2,\rho,N} \) is a continuous semimartingale so that by the Itô-Tanaka formula we find that

\[
(12.16) \quad (b_1^n(\Phi_t^{1,\rho,N}) - \Phi_t^{2,\rho,N})^+ = (b_1^n(\varphi_1) - \varphi_2)^+ \\
+ \int_0^t I(b_1^n(\Phi_s^{1,\rho,N}) > \Phi_s^{2,\rho,N}) \, d(b_1^n(\Phi_s^{1,\rho,N}) - \Phi_s^{2,\rho,N})_s + \frac{1}{2} b_1^n(\Phi_s^{\rho,N})
\]

\[
= (b_1^n(\varphi_1) - \varphi_2)^+ + \int_0^t I(b_1^n(\Phi_s^{1,\rho,N}) > \Phi_s^{2,\rho,N}) \, (b_1^n)'(\Phi_s^{1,\rho,N}) \, d\Phi_s^{1,\rho,N}
\]

\[
+ \frac{1}{2} \int_0^t I(b_1^n(\Phi_s^{1,\rho,N}) > \Phi_s^{2,\rho,N}) \, d\Phi_s^{2,\rho,N} + \frac{1}{2} \ell_t^{b_1^n}(\Phi^{\rho,N})
\]

for \( t \geq 0 \) where \((b_1^n)'\) denotes the first derivative of \( b_1^n \) (its existence follows by the implicit function theorem since smooth fit fails at \( b_1^n \) as pointed out above). Since \( b_1^n \) is convex we see that \( d(b_1^n)' \) defines a non-negative measure on \([1/N, \gamma_n]\) so that the second last integral in (12.16) is non-negative. Using this fact in (12.16) we obtain the following pathwise bound on the size of the local time

\[
(12.17) \quad \ell_t^{b_1^n}(\Phi^{\rho,N}) \leq 2(b_1^n(\Phi_t^{1,\rho,N}) - \Phi_t^{2,\rho,N})^+ - M_t
\]

where \( M_t \) is a continuous martingale (the difference between the second and the final integral in (12.16) above) for \( t \geq 0 \). Taking \( E^0_{\varphi_1, \varphi_2} \) on both sides of (12.17) above and using that \( b_1^n \leq b_1 \) with \( M_N := \sup_{1/N \leq \varphi_1 \leq N} b_1(\varphi_1) < \infty \) we find that

\[
(12.18) \quad E^0_{\varphi_1, \varphi_2}[\ell_t^{b_1^n}] \leq 2M_N
\]

for all \( t \geq 0 \) and all \( n \geq n_0 \) with \((\varphi_1, \varphi_2) \in [0, \infty)^2\).

6. Combining (12.11)+(12.12) with (12.15)+(12.18) we find that \( E^0_{\varphi_1, \varphi_2}[L_t^{n,N}] \to 0 \) as \( n \to \infty \) for every \((\varphi_1, \varphi_2) \in [0, \infty)^2\) and \( N \geq 1 \) given and fixed. Taking \( E^0_{\varphi_1, \varphi_2} \) on both
sides of (12.10), letting \( n \to \infty \) and using the monotone convergence theorem due to \( \hat{H} \geq 0 \), we obtain the following identity

\[
E_{\varphi_1, \varphi_2}^0 \left[ \hat{V}(\varphi_1, \varphi_2) \right] = \hat{V}(\varphi_1, \varphi_2) - E_{\varphi_1, \varphi_2}^0 \left[ \int_0^{t \wedge \rho_N} \hat{H}(\Phi_s) I(\Phi_s \in C) \, ds \right]
\]

for \( t \geq 0 \) and \( N \geq 1 \) with \((\varphi_1, \varphi_2) \in [0, \infty)^2\). Recalling that \( 0 \leq \hat{V} \leq \hat{M} \) where \( \hat{M} \) is defined in (4.13) above, and noting that \( E_{\varphi_1, \varphi_2}^0 (\sup_{0 \leq s \leq t} \phi_i^s) < \infty \) for \( i = 1, 2 \), we see by letting \( N \to \infty \) that the dominated convergence theorem is applicable to the left-hand side of (12.19), while the monotone convergence theorem is applicable to the right-hand side of (12.19) since \( \hat{H} \geq 0 \). Letting \( N \to \infty \) in (12.19) we thus obtain

\[
E_{\varphi_1, \varphi_2}^0 \left[ \hat{V}(\varphi_1, \varphi_2) \right] = \hat{V}(\varphi_1, \varphi_2) - E_{\varphi_1, \varphi_2}^0 \left[ \int_0^{t} \hat{H}(\Phi_s) I(\Phi_s \in C) \, ds \right]
\]

for \( t \geq 0 \) and \((\varphi_1, \varphi_2) \in [0, \infty)^2\).

7. Despite the fact that neither \( (\phi_1^t)_{t \geq 0} \) nor \( (\phi_2^t)_{t \geq 0} \) is uniformly integrable (since \( \Phi_1^t \to 0 \) with \( P_{\varphi_1, \varphi_2} \)-probability one as \( t \to \infty \) but \( \mathbb{E}_{\varphi_1, \varphi_2} (\phi_i^t) = \varphi_i \) for all \( t \geq 0 \) with \( i = 1, 2 \) and \((\varphi_1, \varphi_2) \in (0, \infty)^2 \) given and fixed) we claim that

\[
\{ \hat{M}(\phi_1^t, \phi_2^t) \mid t \geq 0 \}
\]

is uniformly integrable

where we recall that \( \hat{M} \) is defined in (4.13) above. For this, note that \( 0 \leq \hat{M}(\phi_1^t, \phi_2^t) = c \left( (\Phi_1^t + \phi_2^t) \wedge (1 + \phi_1^t) \right) \leq c \left( \phi_1^t + \phi_2^t \right) \) for \( t \geq 0 \). A direct martingale argument based on (5.8) then gives

\[
E_{\varphi_1, \varphi_2}^0 [\phi_1^t \wedge \phi_2^t] = \varphi_1 \varphi_2 \mathbb{E} \left[ e^{\tilde{\mu} W_t^1 - \frac{1}{2} \mu^2 t} e^{\tilde{\mu} W_t^2 - \frac{1}{2} \mu^2 t} \right] \leq \varphi_1 \varphi_2 e^{-\frac{1}{2} \mu^2 t} \mathbb{E} \left[ e^{\frac{\tilde{\mu}}{2} W_t^1 - \frac{1}{2} \mu^2 t} \right] = \varphi_1 \varphi_2 e^{-\frac{1}{2} \mu^2 t} \to 0
\]

as \( t \to \infty \) for \((\varphi_1, \varphi_2) \in [0, \infty)^2\). Since \( \phi_1^t \wedge \phi_2^t \to 0 \) with \( P_{\varphi_1, \varphi_2} \)-probability one as \( t \to \infty \) for \((\varphi_1, \varphi_2) \in (0, \infty)^2 \) given and fixed, we see from (12.22) that \( \{ \phi_1^t \wedge \phi_2^t \mid t \geq 0 \} \) is uniformly integrable. Hence by the bound preceding to (12.22) we see that (12.21) holds as claimed.

8. Since \( 0 \leq \hat{V}(\phi_1^t, \phi_2^t) \leq \hat{M}(\phi_1^t, \phi_2^t) \) for \( t \geq 0 \) we see from (12.21) that \( \{ \hat{V}(\phi_1^t, \phi_2^t) \mid t \geq 0 \} \) is uniformly integrable. Letting \( t \to \infty \) in (12.20) and using that \( \hat{V}(\phi_1^t, \phi_2^t) \to 0 \) with \( P_{\varphi_1, \varphi_2} \)-probability one we thus find by the extended dominated convergence theorem (applied to the left-hand side) and the monotone convergence theorem (applied to the right-hand side) that the following identity holds

\[
\hat{V}(\varphi_1, \varphi_2) = E_{\varphi_1, \varphi_2}^0 \left[ \int_0^{\infty} \hat{H}(\Phi_s) I(\Phi_s \in C) \, ds \right]
\]

\((\varphi_1, \varphi_2) \in [0, \infty)^2\). Combining (12.23) with (12.3) we obtain (12.6) as claimed. Evaluating \( \hat{V} \) from (12.23) at the optimal stopping points \((\varphi_1, b_0(\varphi_1))\) and \((\varphi_1, b_1(\varphi_1))\) upon using that \( \hat{V}(\varphi_1, b_0(\varphi_1)) = \hat{M}(\varphi_1, b_0(\varphi_1)) = \varphi_1 + b_0(\varphi_1) \) and \( \hat{V}(\varphi_1, b_1(\varphi_1)) = \hat{M}(\varphi_1, b_1(\varphi_1)) = 1 + \varphi_1 \) for \( \varphi_1 \in [0, \gamma] \) and \( \varphi_1 \in [0, \infty) \) respectively, we see that the functions \( b_0 \) and \( b_1 \) solve the
integral equations (12.4) and (12.5) as claimed. This completes the proof of the existence of the solution to these equations.

(II) Uniqueness. To show that \( b_0 \) and \( b_1 \) are a unique solution to the system \((12.4)+(12.5)\) one can adopt the four-step procedure from the proof of uniqueness given in [5, Theorem 4.1] extending and further refining the original arguments from [14, Theorem 3.1] in the case of a single boundary. Given that the present setting creates no additional difficulties we will omit further details of this verification and this completes the proof. □

The coupled system of nonlinear Fredholm integral equations \((12.4)+(12.5)\) can be used to find the optimal stopping boundaries \( b_0 \) and \( b_1 \) numerically (using Picard iteration). Inserting these \( b_0 \) and \( b_1 \) into \((12.6)\) we also obtain a closed form expression for the value function \( \hat{V} \).

Collecting the results derived throughout we now disclose the solution to the initial problem.

**Corollary 20.** The value function of the initial problem \((3.3)\) is given by

\[
V(\pi_0, \pi_1, \pi_2) = \pi_0 \hat{V}
\]

for \((\pi_0, \pi_1, \pi_2) \in [0,1]^3\) with \(\pi_0 + \pi_1 + \pi_2 = 1\) where the function \( \hat{V} \) is given by \((12.6)\) above.

The optimal stopping time in the initial problem \((3.3)\) is given by

\[
\tau^* = \inf \\{ t \geq 0 \mid \frac{\pi_i}{\pi_0} e^{\mu(X^i_t - X^0_t)} \geq \frac{\pi_j}{\pi_0} e^{\mu(X^j_t - X^0_t)} \text{ with } \frac{\pi_i}{\pi_0} e^{\mu(X^i_t - X^0_t)} \leq b_0(\frac{\pi_j}{\pi_0} e^{\mu(X^j_t - X^0_t)}) \text{ or } \frac{\pi_i}{\pi_0} e^{\mu(X^i_t - X^0_t)} \geq b_1(\frac{\pi_j}{\pi_0} e^{\mu(X^j_t - X^0_t)}) \text{ for } i \neq j \text{ in } \{1, 2\} \}
\]

where \( b_0 \) and \( b_1 \) are a unique solution to the coupled system of nonlinear Fredholm integral equations \((12.4)+(12.5)\). The optimal decision function \( d_{\tau^*} \) in the initial problem \((3.3)\) equals 0 if stopping in \((12.25)\) happens at \( b_0 \), equals 1 if stopping in \((12.25)\) happens at \( b_1 \) with \( i = 1 \), and equals 2 if stopping in \((12.25)\) happens at \( b_1 \) with \( i = 2 \).

**Proof.** The identity \((12.24)\) was established in (4.11) above. The explicit form \((12.25)\) follows from \((12.7)\) in Theorem 19 combined with \((4.2)-(4.4)\) above. The final claim on the optimal decision function follows from \((3.7)\) combined with the argument used in the second equality of \((4.15)\) above completing the proof. □

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