

# Deep optimal stopping and switching

Approximating the indicator function with NN

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# 1 Introduction

An updated record of the implementations produced can be found at the following link [Optimal Switching](#).

## 2 Optimal stopping problems

The treatment of a sequential decision making setting can be looked at from a more established and traditional perspective, that of an optimal stopping problem. We are interested in finding an optimal control policy that determines when to perform an intervention, given some observed characteristics, so as to maximize the expected total discounted return. It is clear that the problem at hand belong once again to the general class of Markov Decision Processes (MDP).

Fields of application largely include financial strategies (asset selling, hedging) but also sequential hypothesis testing. This topic is also relevant for healthcare applications such as in Ajdari et al. (2019), in determining when to stop the treatment of patients receiving fractionated radiotherapy treatments. Some applications also feature handling of engagement platforms (Liyanage et al. 2019).

### Definition 1: Optimal stopping

Let  $(\Omega, \mathbb{F} = (\mathcal{F})_{n=0}^N, \mathbb{P})$  be a complete probability space, with  $N \in \mathbb{N}$  be a natural number. Consider the time discretization with equidistant time grid  $t_0, t_1, \dots, t_N \in [0, T]$  and  $0 = t_0 < t_1 < \dots < t_N = T$ . The discretization allows for a few simplifications involving the use of simpler algorithms for discrete-state MDP (as opposed to semi/continuous MDP) as well as simplifications regarding the computation of one-step conditional expectations.

Let a  $d$ -dimensional discrete-time Markov process describe the asset price under a Black-Scholes market  $(X_{t_n})_{n=0}^N$  with  $X_0 = x_0$  and be defined on the probability space given:

$$X_t^i = (r - \delta_i)dt + \sigma_i dW_t^i \quad (1)$$

where  $r \in [0, \infty]$  is the market risk free rate,  $\delta_i \in [0, \infty]$  is the dividend yield,  $\sigma_i \in [0, \infty]$  is the volatility and  $W : [0, T] \times \Omega \rightarrow \mathbb{R}^d$  be a standard Brownian motion on the same probability space, with  $i = 1, \dots, d$  stock prices.

Call a random variable  $\tau : \Omega \rightarrow \{t_0, t_1, \dots, t_N\}$  an  $X$ -stopping time if  $\{\tau = n\} \in \mathcal{F}$ . The notion of reward (hence the price) we seek to maximize is:

$$V_n = \sup_{\tau \in \mathcal{T}_n} \mathbb{E}[g(\tau, X_\tau)] \quad (2)$$

where  $\mathcal{T}_n$  denotes the family of all stopping times and  $g(n, X_{t_n})$  is the discounted payoff process.

The problem is then a Markov decision process with state space  $\mathcal{S} = \{0, 1, \dots, N\} \times \mathbb{R}^d \times \{0, 1\}$ , binary action space  $\mathcal{A} = \{0, 1\}$ , where  $a = 0$  stands for holding on the option and  $a = 1$  for stopping the process (e.g. exercising the option) and reward function

$$R((n, X_{t_n}), a) = \begin{cases} g(n, X_{t_n}) & \text{if } a=1 \\ 0 & \text{if } a=0 \end{cases} \quad (3)$$

for  $n = 0, \dots, N$ , transition kernel  $p$  induced by the dynamics of the  $\mathbb{F}$ -Markovian process  $(X_{t_n})_{n=0}^N$ . The state space includes time, the  $d$ -dimensional Markovian process and an absorbing state that captures the event of exercising or not the option, as we do not consider repeated controls.

If perfect knowledge of the MDP is assumed and its size is limited, optimal stopping

problems with finitely many stopping opportunities can be solved exactly, such as with backward induction on binomial/trinomial trees or lattice. It is in fact known that the Snell envelope  $V^*$  provides an optimal solution to 2 (Peskir & Shiryaev 2006):

$$\begin{aligned} U_N &:= g(X_N), \\ U_n &:= \max(g(X_n), \mathbb{E}[\alpha U_{n+1}|X_n]), \end{aligned} \tag{4}$$

where  $\alpha$  is a discount factor. Equivalently,  $U_n$  can be expressed as the optimal stopping problem of the form:

$$U_n = \sup_{\tau \in \mathcal{T}_n} \mathbb{E}[\alpha^{\tau-n} g(X_\tau|X_n)] \tag{5}$$

where  $\mathcal{T}_n$  is the set of all stopping times  $\tau \leq n$ . The associated optimal stopping time  $\tau^*$  is the first time the immediate reward dominates the continuation value:

$$\begin{aligned} \tau_N &:= N, \\ \tau_n &:= \begin{cases} n, & \text{if } g(X_n) \geq \mathbb{E}[\alpha U_{n+1}|X_n] \\ \tau_{n+1}, & \text{otherwise.} \end{cases} \end{aligned} \tag{6}$$

On the other hand, when the state space is large (e.g. when the payoff depends on several underlying assets or when the payoff depends on the history of underlying's prices), the classical algorithms used in the mathematical finance for exotic derivative pricing are no longer computationally tractable. Several approximations methods have been studied in the context of American/Bermudan option pricing, from approximation of the Snell envelope or continuation values (Longstaff & Schwartz 2001, Carriere 1996), to dual methods (Haugh & Kogan 2004). More recently, numerical approximation methods that are based on deep learning have been exploited.

## 2.1 Approximation methods with neural networks

A more recent line of research use backward recursion and stochastic gradient based methods to tackle high dimensional stopping problems. Casting these optimal pricing problems as MDPs allows to tackle them by means of Dynamic Programming or Reinforcement Learning algorithms, thus providing an interesting and valuable alternative to the traditional methods of derivative pricing. In particular, RL tend to be good at handling large state spaces by effectively leveraging sampling and function approximation methodologies in the context of solving the Bellman Optimality Equation, thus breaking the ‘curse of dimensionality’

problem (Rao & Jelvis n.d.).

In the literature there has been proposed two different approaches with respect to the object to be approximated by stochastic gradient based methods. We can distinguish approximation of the continuation value and the indicator function. These methods do not provide theoretical convergence guarantees due to the use of stochastic gradient methods with non-convex loss functions.

#### *Continuation value*

Consider  $m$  realizations from a  $d$ -dimensional Markovian stochastic process  $X$  under  $\mathbb{P}$ , where the  $i$ -th realization is  $x_0, x_1^i, \dots, x_N^i$ , with fixed spot price  $x_0$ . For each  $m$ , the price under stopping strategy 2, can be written as the following backward recursions:

- Tsitsiklis & Van Roy (2001) used the dynamic programming equation on the value function  $p_n^i = \max(g(x_n^i), c_{\theta_n}(x_n^i))$  and estimate directly the current price;
- Longstaff & Schwartz (2001) use the continuation value only for the decision to stop or continue and not for the estimation of the price:

$$\begin{aligned} p_N^i &:= g(x_N^i), \\ p_n^i &:= \begin{cases} g(x_n^i), & \text{if } g(x_n^i) \geq c_n(x_n^i), \\ \alpha p_{n+1}^i, & \text{otherwise.} \end{cases} \end{aligned} \quad (7)$$

where  $c_n(x_n^i)$  is the continuation value. This backward induction method is based on Longstaff & Schwartz (2001)'s results and is the most used in the field.

Originally, both versions in (Longstaff & Schwartz 2001, Tsitsiklis & Van Roy 2001) used a regression estimation of the conditional expectation by expressing the continuation value as  $c_{\theta}(x_n^i) = \theta^T \phi(x_n^i)$ , where  $\phi = (\phi_1, \dots, \phi_K)$  is a set of  $K$  basis functions and  $\theta \in \mathbb{R}^K$  are the weights. More recently, instead, Kohler et al. (2010), Lapeyre & Lelong (2021), Becker et al. (2020) have employed dynamic programming to approximate these with neural networks as:

$$f_{\theta}(x_n^i) \approx c_{\theta}(x_n^i) \quad (8)$$

#### *Indicator function*

In the present survey we will focus on the approximation methods involving the indicator function. Becker et al. (2019) introduced an expression for approximating the indicator function:

$$f_{\theta}(x_n^i) \approx \mathbf{1}_{\{g(x_n^i) \geq c(x_n^i)\}} \quad (9)$$

This allows to estimate the current price as:

$$p_n^i = g(x_n^i) f_{\theta_n}(x_n^i) + \alpha p_{n+1}^i (1 - f_{\theta_k}(x_n^i)) \quad (10)$$

The optimization involves directly the option price  $\psi_n(\theta_n) = \frac{1}{m} \sum_{i=1}^m \alpha p_n^i$ .

### 3 Optimal switching

Consider now an optimal switching problem, that is finding the optimal sequence of opening (starting) and closing (stopping) times of a multi-actions sequential process. Problems of this nature have arisen naturally in domains such as when evaluating the profitability of an investment in the natural resource industry where the production depends on the market price of a number of underlying commodities or assets (Brennan & Schwartz 1985). Since this early work, there have been proposed several extensions looking at different aspects such as the model describing the underlying commodity  $X$  as being a diffusion process for example (Knudsen et al. 1998, Zervos 2003) or looking at different choices for the filtration to which the stochastic process is adapted to (Hamadene & Hdhiri 2006, Hamadène & Jeanblanc 2007). This framework can also take into account of real-world approximation of constraints (e.g. resource allocation in a hospital facility) referred to as costs of opening, running, and closing the activities.

At the following links, I have included two versions of the optimal switching problem, either fixing the final regime and considering both options, , .

### Definition 2: Optimal switching

Let  $(\Omega, \mathcal{F}, \mathbb{P})$  be a complete probability space with filtration  $\mathbb{F} = (\mathcal{F}_t)_{t \in \mathbb{T}}$  and integer-valued finite times  $\mathbb{T} = \{0, 1, \dots, T\}$  for the discretization of the process. In addition, the setup includes the following problem-specific elements:

- a discrete set of operational modes  $\mathbb{I} = \{1, 2, \dots, q\}$ , where  $2 \leq q < \infty$ . In this case we consider  $q = 2$  with  $\mathbb{I} = \{\text{on}, \text{off}\}$ , which could represent "start/stop" of a treatment, "admission/non-admission" to ICU
- a final reward received at time  $T$  for being in mode  $i \in \mathbb{I}$ , which is modelled by an  $\mathcal{F}_T$ -measurable real-valued random variable  $\Gamma_i$
- a running reward (payoff rate per unit of time) received while in mode  $i \in \mathbb{I}$ , which is modelled by a real-valued adapted process as a mapping  $\Psi_i(t, X_t) : \Omega \times [0, T] \rightarrow \mathbb{R}$
- a cost for switching from mode  $i \in \mathbb{I}$  to  $j \in \mathbb{I}$ , which is modelled by a real-valued adapted process  $\gamma_{i,j} : \Omega \times [0, T] \rightarrow \mathbb{R}$  to cover for the extra costs due to the change of the regime.

A strategy  $\alpha$  for the system will be a combination of two sequences:

- non decreasing sequence of  $\mathbb{F}$ -stopping times  $(\tau_n)_{n \geq 1}$ ,  $n \in \mathbb{N} \setminus \{0\}$ , where at  $\tau_n$  the production is switched from the current mode  $i$  to  $j$ . we also assume:  $\tau_0 = t$  and  $\tau_n \leq \tau_{n+1}$
- a sequence of indicators  $(\iota_n)_{n \geq 1}$ ,  $n \in \mathbb{N} \setminus \{0\}$ ,  $\mathcal{F}_{\tau_n}$ -measurable valued in  $\mathbb{I}_q$ . At time  $t = \tau_n$  the system is switched from the current regime  $\iota_{n-1}$  to  $\iota_n$ , with  $\iota_0 = i$ .

We denote by  $\mathcal{A}_{t,i}$  the set of admissible strategies to switch at time  $\tau_n$ ,  $n \geq 1$ , from the current regime  $\iota_{n-1}$  to  $\iota_n$ .

For any initial condition  $(x, i) \in [0, T] \times \mathbb{I}_q$ , and any control  $\alpha = (\tau_n, \iota_n)_{n \geq 0} \in \mathcal{A}_{t,i}$ , the total expected profit up to  $T$  for such strategy can be expressed as  $J(\alpha; t, i)$ . Given the costs and rewards elements listed above, the profit for such strategy is:

$$J(\alpha : t, i) = \mathbb{E} \left[ \sum_{s=t}^{T-1} \Psi(X_s^{x,i}, I_s^i) + \Gamma - \sum_{n \leq 1} \gamma_{\iota_{n-1}, \iota_n} \mathbf{1}_{\{\tau_n < T\}} | \mathcal{F}_n \right] \quad (11)$$

The optimal switching problem is to maximize this expected total profit for all strategies

$\alpha \in \mathcal{A}_{t,i}$ . For this purpose, we set the value function:

$$V_i(x) = \sup_{\alpha \in \mathcal{A}} J(\alpha : t, i) \quad \forall \alpha \in \mathcal{A}_{t,i} \text{ } \mathbb{P} \text{ a.s.} \quad (12)$$

A switching control  $\alpha^* \in \mathcal{A}_{t,i}$  is said to be optimal if it achieves the essential supremum in 28:  $V_i(x) = J(\alpha^*; t, i) \geq J(\alpha; t, i), \forall \alpha \in \mathcal{A}_{t,i} \text{ } \mathbb{P} \text{ a.s.}$ . Reconciling notation from section Becker et al. (2019), we can identify the expression under the expectation in 11 as a form of the discounted profit  $g(\alpha, X_\alpha)$ , which is a function of  $\alpha$ . We will use an iterative version obtained from the discrete-time adaptation to the continuous-time verification theorem (Djehiche et al. 2009, Martyr 2016). In terms of a verification theorem, it is possible to show the existence of  $q$  real-valued adapted processes  $Y^1, \dots, Y^q$  solutions of a system of equations derived from the Snell envelopes. Denote by  $Y_t^i$ , for  $i \in \mathbb{I}$ , as the optimal expected profit if, at time  $t$ , the regime is in state  $i$ :

$$\begin{aligned} \tilde{Y}_T^i &= \Gamma_i \\ \tilde{Y}_t^i &= \max_{i \neq j} \{-\gamma_{i,j}(t) + \Psi_j(t) + \mathbb{E}[\tilde{Y}_{t+1}^j | \mathcal{F}_t]\} \wedge \{\Psi_j(t) + \mathbb{E}[\tilde{Y}_{t+1}^i | \mathcal{F}_t]\} \text{ for } t < T \end{aligned} \quad (13)$$

## 4 Approximating the indicator function

We will follow the same approach proposed by Becker et al. (2019) to produce an estimate for the value in 28. This can be achieved in the following two steps.

### 4.1 0-1 decisions and optimization

Following Becker et al. (2019), we break down the problem in ?? into a sequence of time  $n$  stopping problems  $V_n = \sup_{\tau \in \mathcal{T}_n} \mathbb{E}g(\tau, X_\tau)$ , where  $\mathcal{T}_n$  is the set of all  $X$ -stopping times such that  $n \leq \tau \leq N$ . The decision to stop the Markov process can be made according to a sequence of functions  $\{f_n(X_n)\} : f_n : \mathbb{R}^d \rightarrow \{0, 1\}, n \in \mathbb{N}$ , hence representing indicators functions.

At this point we are interested in producing an expression for  $\tau_n$  as a function of  $\{f_n(X_n)\}$ :

- at maturity we fix a stopping decision, this implies  $f_N \equiv 1$ , hence  $\tau_N \equiv N$  or  $\tau_N \equiv Nf_N(X_N)$ , the unique element in  $\mathcal{T}_N$



- for  $n < N$ , we can write  $\tau_n$

$$\tau_n = \sum_{m=n}^N m f_m(X_m) \prod_{j=n}^{m-1} (1 - f_j(X_j)) \in \mathcal{T}_n \quad (14)$$

While it is clear that  $\tau_N$  is the time  $N$  optimal stopping time, the same needs to be demonstrated for  $\tau_n$ . In particular we have that  $\tau = \sum_{n=1}^N n f_n(X_n) \prod_{j=0}^{n-1} (1 - f_j(X_j))$  is an optimal stopping time for  $??$ . See Appendix A for more details.

#### 4.2 Neural network

To approach the problem, we iteratively approximate the optimal stopping decisions  $f_n : \mathbb{R}^d \rightarrow \{0, 1\}, n = \{1, \dots, N - 1\}$ , by a neural network  $f^\theta : \mathbb{R}^d \rightarrow \{0, 1\}$  with parameter  $\theta \in \mathbb{R}^q$ . We choose  $\theta_N \in \mathbb{R}^q$  such that  $f_N^\theta \equiv 1$  and determine  $\theta_n \in \mathbb{R}^q$  for  $n \leq N - 1$  by recursion of the form:

$$\tau_{n+1} = \sum_{m=n+1}^N m f_m^{\theta_m}(X_m) \prod_{j=n+1}^{m-1} (1 - f_j^{\theta_j}(X_j)) \quad (15)$$

Since  $f^\theta$  takes values in  $\{0, 1\}$ , hence not appropriate for a gradient-descent optimization method, the neural network includes a layer performing a logistic transformation such that we have a continuous output function  $F^\theta : \mathbb{R}^d \rightarrow (0, 1)$ .

The Neural network includes  $(d + 40)$  hidden units and comprises a combination of linear functions  $a_i^\theta(x) = W_i x + b_i$ , rectified linear activation functions  $\phi_{q_i}(x_1, \dots, x_{q_i}) = (x_1^+, \dots, x_{q_i}^+)$ , and a final logistic sigmoid function  $\psi(x) = 1/(1 + e^{-x})$ ,  $??$ . The parameters that are being tuned are  $\theta = \{W_1, W_2, W_3, b_1, b_2, b_3\} \in \mathbb{R}^q$  and  $q = q_1(d + q_2 + 1) + 2q_2 + 1$ .

At each time step, for each epoch we compute  $F^{\theta_n}$  using the  $\theta_n$  from the previous epoch. Then, the parameter  $\theta_n$  is update via backpropagation by the gradient of the loss function (Adam optimization algorithm (Kingma & Ba 2014)), which is specified as:

$$Loss = -\mathbb{E}[g(n, X_n) F^{\theta_n}(X_n) + g(\tau_{n+1}, X_{\tau_{n+1}})(1 - F^{\theta_n}(X_n))] \quad (16)$$

The aim is to determine  $\theta_n \in \mathbb{R}^q$  so that the negative of the loss function is close to the supremum  $\sup_{\theta \in \mathbb{R}^q} \mathbb{E}[g(n, X_n) F^\theta(X_n) + g(\tau_{n+1}, X_{\tau_{n+1}})(1 - F^\theta(X_n))]$ . From the stopping probabilities  $F^{\theta_n}$ , we retrieve  $f^{\theta_n}$  as hard decisions  $\{0, 1\}$ .

Once the optimal  $\theta^n$  is computed for all time steps  $n$  it is straightforward to obtain the desired estimate for the value function in  $??$ , given some assumptions on the hyperparame-

ters and payoff function.

## 5 An application of the optimal switching problem

Building upon the problem formulation presented by Becker et al. (2019), the optimal switching architecture will adopt the same probabilistic setup and similar assumptions as per being a finite-horizon discrete-time model pricing a Bermudan call option. Here we present an implementation of the switching problem with start and stop decision and derive a lower bound for the optimal value  $V_0$ . We will consider two versions:

- a simpler version where we fix the final regime and proceed backwards along a single path
- a larger version where we follow two paths at the same time, differing in their final regime at maturity. At the moment, this second version is producing non-correct values.

### 5.1 Training

To approach the estimation of this iteration, we can start by providing a simulation of the process. For simplicity, we suppose a Bermudan max-call option expiring at time  $T$  is written on  $d$  assets,  $\{X^i\}_{i=1}^d$ , that gives the option holder the right to purchase one of the  $d$  assets at strike price  $K$  at any point in time on the time grid  $0 = t_0 > t_1 > \dots > t_N = T$ ,  $t_n = n \cdot T/N$ . We assume the following expression for the various cost and benefit:

- Terminal function  $\Gamma_i(N)$  is set to the option payoff. The terminal payoff is received at maturity, with no other costs nor payoffs

$$\begin{aligned}\Gamma_0(N) &= 0 \\ \Gamma_1(N) &= \left( \max_{i \in \{1, \dots, d\}} x^i - K \right)^+\end{aligned}\tag{17}$$

- Running reward  $\Psi_q = (\Psi_q(n))_{n \in \mathbb{N}}$  received while in mode  $q \in \mathbb{I}$ .

$$\Psi_q(n) = \left[ \left( \max_{i \in \{1, \dots, d\}} x_n^i - K \right)^+ \right]^{k_q} \quad k \in \{.4, .7\}\tag{18}$$

- Switching cost  $\gamma_{i,j} = (\gamma_{i,j}(n))_{n \in \mathbb{N}}$  with  $i, j \in \mathbb{I} = \{0, 1\}$  represents the cost for switch-

ing from mode  $i \in \mathbb{I}$  to mode  $j \in \mathbb{I}$ .

$$\begin{aligned}\gamma_{0,0} &\equiv \gamma_{1,1} \equiv 0 \\ \gamma_{0,1}(n) &= \left( \max_{i \in \{1, \dots, d\}} x^i - K \right)^+ + \delta, \quad \delta \sim \mathcal{N}(0, 1) \\ \gamma_{1,0}(n) &= - \left( \max_{i \in \{1, \dots, d\}} x^i - K \right)^+\end{aligned}\tag{19}$$

We can introduce a discount factor  $e^{-\rho t_n}$  and consider the discounted discrete-time optimal switching problem at time 0 starting in mode  $i \in 0, 1$ , defined as:

$$\begin{aligned}J(\alpha; 0, i) &= \mathbb{E} \left[ e^{-\rho T} \Gamma_{i_{N(\alpha)}} - \sum_{n \geq 1} e^{-\rho \tau_n (T/N)} \gamma_{\iota_{n-1}, \iota_n}(\tau_n) \mathbf{1}_{\{\tau_n < T\}} \right] \\ V(i) &= \sup_{\alpha \in \mathcal{A}_{0,1}} J(\alpha; 0, i)\end{aligned}\tag{20}$$

Now we can adjust the notation to follow more closely Becker et al. (2019)'s notation. Since the option can be exercised only at  $t_0, t_1, \dots, t_N$ , we can write the price as  $\sup_{\alpha \in \mathcal{A}_{0,1}} \mathbb{E}g(\tau, X_\tau)$  where

$$g(n, x) = e^{-\rho t_N} \Gamma_{i_{N(\alpha)}} - \sum_{t_n \geq 1} e^{-\rho t_n} \gamma_{\iota_{t_{n-1}}, \iota_{t_n}}(t_n) \mathbf{1}_{\{t_n < t_N\}}\tag{21}$$

We will still rely on the recursive expression

$$\begin{aligned}\hat{Y}_N^i &= \Gamma_i \\ \hat{Y}_n^i &= \max_{j \in [0,1]} \{ -\gamma_{i,j}(n) + \mathbb{E}[e^{-\rho h} \hat{Y}_{n+1}^j | \hat{\mathcal{F}}_n] \} \quad \text{for } n = N-1, \dots, 0\end{aligned}\tag{22}$$

We can then rewrite the optimal switching problem as

## 5.2 Training

Simulate  $d+1$ -dimensional asset prices  $(Y_n)_{n=0}^N$  according to 1 as follows:

$$y_{n,i}^m = y_{0,i} \cdot \exp \left\{ \sum_{k=0}^n \left( (r - \delta_i - \sigma_i^2/2) \Delta t + \sigma_i \sqrt{\Delta t} Z_{k,i}^m \right) \right\}\tag{23}$$

where  $\Delta t = T/N$  and  $Z_{k,i}^m \sim \mathcal{N}(0, 1)$ . In this example, for  $i = \{2, 3, 5, 10, 20, 30\}$  assets, take

$$y_0^1 = \{90, 100, 110\}, \quad K = 90, \quad \sigma = 20, \quad d = 10, \quad r = 5, \quad T = 3, \quad N = 9,$$

The system can be switched on or off at any point of a time grid  $0 = t_0 < t_1 < \dots < t_N$  and its value is given by

$$Y_n^i = \text{ess sup}_{\tau \in \mathcal{T}_n} \mathbb{E}g(\tau, X_\tau, ) \quad (24)$$

where the payoff function  $g$  can be expressed as:

$$g(n, X_n, \mathbb{I}) = \max_{j \neq i} \{ -\gamma_{i,j}(n) + \Psi_j(n) + \mathbb{E}[Y_{n+1}^j | \mathcal{F}_n] \} \vee \{ \Psi_j(n) + \mathbb{E}[Y_{n+1}^i | \mathcal{F}_n] \} \quad (25)$$

Since  $Y_0$  is deterministic, we can train the stopping times  $\tau_1 \in \mathcal{T}_1$  as

$$\tau_1 = \sum_{n=1}^N n f^{\theta_n}(Y_n) \prod_{j=1}^{n-1} (1 - f^{\theta_j}(Y_j)) \quad (26)$$

for  $f^{\theta_N} \equiv 1$  and  $f^{\theta_1}, \dots, f^{\theta_{N-1}} : \mathbb{R}^{d+1} \rightarrow \{0, 1\}$  given by the logit transform of  $F^{\theta_n}$  with  $\mathbb{I} = 2$  and  $q_1 = q_2 = d + 40$ . The candidate optimal stopping time is

$$\tau^\Theta = \begin{cases} 0 & \text{if } f_0 = 1 \\ \tau_1 & \text{if } f_0 = 0 \end{cases} \quad (27)$$

### 5.3 Testing - Lower bound

d	$X_0$	Lower bound	Time	Results
2	90	97.339	0.009	
2	100	205.426	0.006	
2	110	315.878	0.007	
4	90	130.082	0.008	
4	100	235.951	0.008	
4	110	334.079	0.005	
5	90	134.486	0.008	
5	100	224.051	0.006	
5	110	282.737	0.006	
10	90	158.875	0.005	
10	100	273.452	0.008	
10	110	391.043	0.015	
20	90	100.447	0.008	
20	100	192.448	0.01	
20	110	301.107	0.009	

### 5.4 Testing - Upper bound

# Appendices

## A Theorem

For a given  $n \in \{0, 1, \dots, N-1\}$ , let  $\tau_{n+1}$  be a stopping time in  $\mathcal{T}_{n+1}$  of the form

$$\tau_{n+1} = \sum_{m=n+1}^N m f_m(X_m) \prod_{j=n+1}^{m-1} (1 - f_j(X_j)) \quad (28)$$

for measurable functions  $f_{n+1}, \dots, f_N : \mathbb{R}^d \rightarrow \{0, 1\}$  with  $f_N \equiv 1$ . Then, there exists a measurable function  $f_n : \mathbb{R}^d \rightarrow \{0, 1\}$  such that  $\tau_n \in \mathcal{T}_n$  satisfies

$$\mathbb{R}g(\tau_n, X_{\tau_n}) \geq V_n - (V_{n+1} - \mathbb{E}g(\tau_{n+1}, X_{\tau_{n+1}})) \quad (29)$$

where  $V_n$  and  $V_{n+1}$  satisfy ???. It follows that the overall optimal stopping time for ?? is

$$\tau = \sum_{n=1}^N n f_n(X_n) \prod_{k=0}^{n-1} (1 - f_k(X_k)) \quad (30)$$

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