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# Finding the $\kappa$ best out of $n$ rankable objects. A consecutive thresholds Algorithm

F. Thomas Bruss\*      Guy Louchard †

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## Abstract

The objective of this paper is to find in a setting of  $n$  sequential observations of objects a good online policy to select the  $\kappa$  best of these  $n$  uniquely rankable objects. This focus is motivated by the fact that it is hard to find closed form solutions of optimal strategies for general  $\kappa$  and  $n$ . Selection is without recall, and the idea is to investigate threshold functions which maintain all present information, that is thresholds which are functions of all selections made so far. Our main interest lies in the asymptotic behaviour of these thresholds as  $n \rightarrow \infty$  and in the corresponding asymptotic performance of the threshold algorithm.

**Keywords:** Multiple stopping rule, secretary problem, monotonicity, unimodality, relative ranks, record-values, optimality.

**2010 Mathematics Subject Classification:** 60G40 (68W27).

## 1 Introduction

The so-called secretary problem is a classical problem of optimal stopping on a sequence of rankable observations. It is the problem of choosing the best of  $n$  rankable options appearing in random arrival order with probability  $1/n!$  each. It was first solved by Lindley [8] in 1961. See e.g. Ferguson [7] for an interesting review. This is the special case  $\kappa = 1$  of the problem we consider here, namely to find with one stop without recall the best of  $n$  uniquely rankable objects or options. Arguably the shortest solution to this problem is provided by the more general odds-theorem of optimal stopping (Bruss [2]).

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\*Université Libre de Bruxelles, Département de Mathématique , CP 210 Boulevard du Triomphe, B-1050 Bruxelles, Belgium, [tbruss@ulb.ac.be](mailto:tbruss@ulb.ac.be)

†Université Libre de Bruxelles, Département d'Informatique, CP 212, Boulevard du Triomphe, B-1050 Bruxelles, Belgium, [louchard@ulb.ac.be](mailto:louchard@ulb.ac.be)

The optimal strategy is to wait until the threshold index  $s \in N$  and to accept the first relative rank 1 from  $s$  onwards (if any). Here  $s$  is defined as the smallest  $m \in N$  such that  $\sum_{j=m}^n r_j \geq 1$  where  $r_j$  denotes the odds of the  $j$ th event being a candidate for stopping. If no such  $m$  exists, then  $s := 1$  by definition.

For the classical secretary problem  $r_j = (1/j)/(1 - 1/j) = 1/(j - 1)$  because the best candidate among the first  $j$  is the  $j$ th in chronological order with probability  $1/j$ . The corresponding win probability is then

$$V_n = \frac{s-1}{n} \sum_{j=s-1}^{n-1} \frac{1}{j}.$$

Putting  $s := s(n)$  it is well-known that  $\lim_{n \rightarrow \infty} s_n/n = 1/e$ .  $V_n$  has the same limit as the function  $s_n/n$ , namely  $1/e$ . Interestingly, (Bruss [3]), the value  $1/e$  is also the precise lower bound in much more general problems of stopping with maximum probability on *any* last specific event. For a further generalization see the review by Dendievel [6].

The problem of making the  $\kappa$  best choices, or in short the  $\kappa$ -best problem, is to find an efficient stopping rule to select (all) the  $\kappa$  best objects online from a sequence of  $n$  objects. The study of this problem is the main objective of the present paper. Indeed, if  $\kappa > 1$  then the optimal solution as well as the limiting behaviour of the thresholds seem difficult. Actually, one would not expect such a difficulty because one may intuitively expect some recursive structure. Such a structure is there, of course, but a little reflection shows that once one has selected  $1 \leq \kappa' < \kappa$  objects, the optimal continuation does not only depend  $\kappa - \kappa'$  but also on the values of the chosen ones. This difficulty motivated several authors before, and the present paper complements earlier results by Vanderbei [13] and Tamaki [12] by an independent approach rather than really solving it. However, as we shall argue, this complement has interest on its own.

### Related work

Platen [9] studies the problem of choosing a fixed number of objects (secretaries) from a sequence of  $n$  but his objective function is different. He thinks of the rank  $k$  as generating the cost  $k$  and considers the problem of minimizing the sum of the cost of all selections. Notice that this is different from the problem of minimizing the expected rank as studied by Chow et al [5] and also again quite different from our problem of maximizing the expected payoff of one if and only if all the  $\kappa$  best objects are chosen, and zero otherwise. Platen also considers more general payoff (cost) functions, but, motivated by thinking of secretary problems, limits his interest to additive functions, which do not apply to our problem.

A more weakly related problem has been studied by Rose [10] for the case  $\kappa = 2$ . Rose introduces in the same model two decision makers, one of which is defined as dominant. The objective is to select the two best objects, the best one being assigned to the dominant decision maker. Rose considers a strategy as successful if and only if both decision

makers reach their goal under the online assignment constraint. Hence here the optimal success probability should be (and is, as we shall see) smaller than in our problem without assignments. Note also that the concurrent assignment constraint gives Roses' problem quite a different character.

Another  $\kappa$ -choice problem was studied by Anô et al. [1] who maximise the probability of finding the *best* candidate with  $\kappa$  available sequential choices. Szajowski and Lebek [11] solve an interesting related investment problem for  $\kappa = 2$ .

Wilson [15] generalizes the model of Rose for general  $\kappa$ , also with simultaneous online assignment of ranks. The paper displays important optimality conditions for general  $\kappa$ , but closed-form solutions seem now to become hard.

Tamaki [12] looks at the same problem for  $\kappa = 3$  and shows that, interestingly, in contrast to the case  $\kappa = 1$  (secretary problem) and the case  $\kappa = 2$  the optimal strategy is now no longer simple. Here *simple* means that, for the  $\kappa$  selections, the strategy waits until a threshold index  $s_k$  and selects then consecutively the next  $k$  (if possible) record candidates. Tamaki's observation of the non-simplicity of the optimal rule for  $\kappa = 3$  (and  $\kappa \geq 3$ ) is important in this context because it gives additional motivation to the work of the approach presented in this paper as well as to earlier work of Vanderbei [13] described below.

Vanderbei [13] studies the corresponding problem without online assignments with an original approach by formulating the problem as a control problem defined on a Markov chain. An explicit solution is found for  $n$  even and  $\kappa = n/2$ . The corresponding optimal win probability equals  $\frac{1}{n/2+1}$ . For general  $\kappa$ , this article confines its interest to studying a simple sub-optimal solution. Thus Vanderbei studies the same problem as ours but the approach is different. As far as we understand, Vanderbei's sufficient condition (see the last line of [13] p.481) is not a sufficient condition in the set of strategies which we consider. Indeed, we need in general also information about 2-records, 3-records, up to  $(\kappa - 1)$ -records, where a  $s$ -record is a candidate which is at the time of its arrival of relative rank  $s$ . Having said this we see by Theorem 5.1 of [13] that the sufficient condition we require is implicit by the definition of "marginal", and the definition of the sets  $T$  and  $S'$ , so that our strategies may coincide. A closer comparison between approaches is difficult, however, since Vanderbei's approach leads to a difference-differential equation (see (5.3) in [13]) whereas our approach is purely algorithmic. Without being able to say more in definite terms, we think of our contribution as of being an attractive alternative to Vanderbei's result and as a way of access to a *good* solution for *general*  $\kappa$ .

Let us finally mention another interesting result by Vanderbei [14]. In this paper, he considers a minor variant of this classical secretary problem. He wishes to pick not the best but the second best postdoc (the best is going to Harvard). In this case, an explicit solution can be given both for the optimal strategy and the associated optimal success probability. The probability of success is  $k_0(n - k_0)/(n(n - 1))$ , where  $k_0 = \lfloor n/2 \rfloor$ . Clearly, as  $n$  goes to infinity, the probability of success tends to  $1/4$ . Hence, it is easier to pick the best than the second best, a phenomenon which is not only true in several other selection

problems but, often enough, felt to be true in real life.

## 1.1 Algorithm

The approach to the algorithm we will propose consists of two parts: firstly, defining a suitable strategy, secondly, computing sequentially the necessary parameters we have to plug in. We are interested in understanding the asymptotic form of an optimal or, at least, efficient, strategy, and its corresponding value as  $n \rightarrow \infty$ .

### The $\kappa$ choices threshold strategy:

Our strategy, based on thresholds, is defined as follows:

we use  $\kappa$  thresholds:  $1 \leq j_1 < j_2 < \dots < j_\kappa \leq n$ . The way we compute these thresholds will be characterized later on. It will turn out that there are no general closed forms for the optimum values for these thresholds.

Following Vanderbei's terminology, we define first two kinds of candidates:

1. *compulsory candidates* i.e. candidates whom we *must* retain, given the ranks of the candidates we have already chosen. For instance, if we have chosen so far  $\ell$  candidates, ranked  $1 < 2 < \dots < \ell$  (rank 1 corresponds to the best candidate, rank 2 to the second best, etc.), we *must* retain any candidate with relative rank  $\leq \ell$ .
2. *marginal candidates* i.e. candidates whose relative rank is less than or equal to  $\ell + 1$ .

According to our strategy, we first choose the first record (if any) arriving at position  $u_1 \geq j_1$ . This is done for all possible values of  $j_1$  where  $j_1$  is some index between 1 and  $n$ . We then compute for each possible position  $u_1$  an optimal threshold  $j_2(u_1) \geq u_1$ . The reason behind this is that we have two possibilities, namely:

1. We observe a *compulsory candidate* at position  $u_2 < j_2$ . We take this candidate and we start again the strategy at position  $u_2$ , with a new threshold  $j_3(u_2)$ . The strategy iterates then this procedure accordingly over the position values. At this stage it is difficult to say already more, and the details are postponed to the beginning of Sec.3.
2. We do not observe any *compulsory candidate* before  $j_2$ . Then, from  $j_2$  on, we retain a *compulsory candidate* or a *marginal candidate* (if any) at position  $u_2$ . We now start again the strategy at position  $u_2$ , with a new threshold  $j_3(u_2)$  and, as before, we iterate the procedure.

### Examples

To give an example, we first define the 2-choice strategy. We define a  $(j_1, j_2)$ -strategy as the policy to act as follows:

1. wait until index  $j_1$  without any action;
2. select, from  $j_1$  onwards, the first record (if any). Thereafter instructions will split according to two possibilities:
3. (a) if we select only one record value up to a certain index  $j_2 \in (u_1, n)$  then we accept a record value or 2-record value after  $j_2$ ,  
or else,  
(b) we select two consecutive records up to  $j_2$  (if any.)

For  $\kappa = 3$ , the definition of a  $(j_1, j_2, j_3)$ -strategy if  $\kappa = 3$  is in principle analogous but, again, it is better to postpone the details to the beginning of Sec.3. The corresponding optimal thresholds are denoted by  $j_1^*, j_2^*, j_3^*$ . The order of computation is backwards.

The asymptotic results for  $\kappa = 2$  and  $\kappa = 3$  are summarized in the following theorem:

**Theorem 1.1** • With  $j_1^* = j_1^*(n)$ ,  $j_2^* = j_2^*(n)$ , the optimal thresholds  $j_1^*$  and  $j_2^*$  for the case  $\kappa = 2$  satisfy the asymptotic relationship

$$j_1^*/n \rightarrow -e^{-1/2}W(-\exp(-3 + e^{1/2})) = 0.2291147286\dots$$

where  $W(x)$  is the Lambert's function ,

$$j_2^*/n \rightarrow e^{-1/2} = 0.6065306596\dots,$$

The asymptotic success probability of the  $(j_1^*, j_2^*)$ -strategy equals  $0.2254366561\dots$

- In the case  $\kappa = 3$  , the corresponding asymptotic relationships are

$$j_1^*/n \rightarrow .1666171752\dots,$$

$$j_2^*/n \rightarrow -e^{-1/3}W(-\exp(-5/2 + e^{1/3})) = .4369818602\dots,$$

$$j_3^*/n \rightarrow e^{-1/3} = .7165313106\dots,$$

and the asymptotic success probability of the  $(j_1^*, j_2^*, j_3^*)$ -strategy equals  $.1625200069\dots$

Our computational technique can be extended to any  $\kappa$ . We will illustrate the optimal thresholds computation and analyze the performance, i.e. the success probability of our algorithm for the cases  $\kappa = 2, \kappa = 3$ .

## 2 The case $\kappa = 2$

Let us first compute  $j_2(u_1) \geq u_1$ , given  $u_1$ . In order to simplify our expressions, we will introduce a function  $G(a, b, c)$ :

$$G(a, b, c) := \prod_{k=a}^b \left(1 - \frac{c}{k}\right) = \frac{(a-1)^c}{b^c}.$$

As explained in Sec.1, we have two possibilities:  $u_1 < j_2 \leq u_2$ , or, alternatively,  $u_1 < u_2 < j_2$ .

The probability of success of the first case is given by

$$\begin{aligned} & \sum_{u_2=j_2}^n \prod_{k=u_1+1}^{j_2-1} \left(1 - \frac{1}{k}\right) \prod_{\ell=j_2}^{u_2-1} \left(1 - \frac{2}{\ell}\right) \frac{2}{u_2} \prod_{s=u_2+1}^n \left(1 - \frac{2}{s}\right) \\ &= \sum_{u_2=j_2}^n G(u_1+1, j_2-1, 1) G(j_2, u_2-1, 2) \frac{2}{u_2} G(u_2+1, n, 2) \\ &= \sum_{u_2=j_2}^n \frac{u_1}{n} \frac{2}{u_2-2} \frac{j_2-2}{n-1} =: u_1 F_1(u_1, j_2) \text{ say .} \end{aligned}$$

To see this note that after index  $j_2$ , we have two possible types of *candidates*, a *compulsory* or a *marginal* candidate at position  $u_2$ . After  $u_2$ , we must exclude any *compulsory candidate*.

We note that  $u_1 F_1(u_1, j_2)$  is unimodal in  $j_2$  because  $u_1 F_1(u_1, j_2) - u_1 F_1(u_1, j_2 - 1)$  yields after a few steps of simplification the form

$$\frac{1}{n(n-1)} 2u_1 \left(1 - \sum_{u_2=j_2+1}^n \frac{1}{u_2-2}\right)$$

which changes sign at most once according to the value  $j_2$ .

The probability of success of the second case is given by

$$\begin{aligned} & \sum_{u_2=u_1+1}^{j_2-1} \prod_{k=u_1+1}^{u_2-1} \left(1 - \frac{1}{k}\right) \frac{1}{u_2} \prod_{\ell=u_2+1}^n \left(1 - \frac{2}{\ell}\right) \\ &= \sum_{u_2=u_1+1}^{j_2-1} G(u_1+1, u_2-1, 1) \frac{1}{u_2} G(u_2+1, n, 2) \\ &= \sum_{u_2=u_1+1}^{j_2-1} \frac{u_1}{n(n-1)} =: u_1 F_2(u_1, j_2) \text{ say .} \end{aligned}$$

Here we note that after  $u_1$  and before  $j_2$ , we have one possible *compulsory candidate* at position  $u_2$ . After  $u_2$ , we must exclude any *compulsory candidates*.  $u_1 F_2(u_1, j_2)$  is clearly monotone in  $j_2$  because it is, as seen in the last sum term, affine linear in  $j_2$ . Consequently  $u_1 F_1(u_1, j_2) + u_1 F_2(u_1, j_2)$  is unimodal in  $j_2$  because the sum of a unimodal function and an affine linear function is unimodal.

Of course,  $F_2(u_1, j_2)$  is quite simple here, but, viewing general  $\kappa$ , we prefer to keep a general notation.

As  $n \rightarrow \infty$ , we use the Euler Maclaurin formula to replace sums by integrals (see also the continuous-time model Tamaki [12]). Moreover, we use continuous variables  $u'_1 := u_1/n, u'_2 := u_2/n, \dots$ . By a slight abuse of notations, in order to simplify our expressions, we will continue to use  $u_1, u_2, \dots$  as continuous time variables.

Since both parts contributing to the win probability have the same factor  $u_1$ , it now suffices to maximize the sum  $F_1(u_1, j_2) + F_2(u_1, j_2)$ , conditioning on  $u_1$ , that is we must maximize the asymptotic expression

$$V_1(u_1, j_2) := \int_{j_2}^1 2 \frac{j_2}{u_2} du_2 + \int_{u_1}^{j_2} 1 du_2 = -u_1 + j_2 - 2j_2 \ln(j_2). \quad (1)$$

This gives  $j_2^* = e^{-1/2} = 0.6065306596 \dots$

We note that  $V_1(u_1, j_2)$  can be seen as the sum of two functions  $\varphi_1(u_1)$  and  $\varphi_2(j_2)$  namely  $\varphi_1(u_1) + \varphi_2(j_2)$ . Since  $\frac{d\varphi_2(j_2)}{dj_2} = 1 - 2 \ln(j_2) - 2$  is monotone in  $j_2$ , the function  $\varphi_2$  is unimodal. A plot of  $\varphi_2(j_2)$  is given in Figure 1.

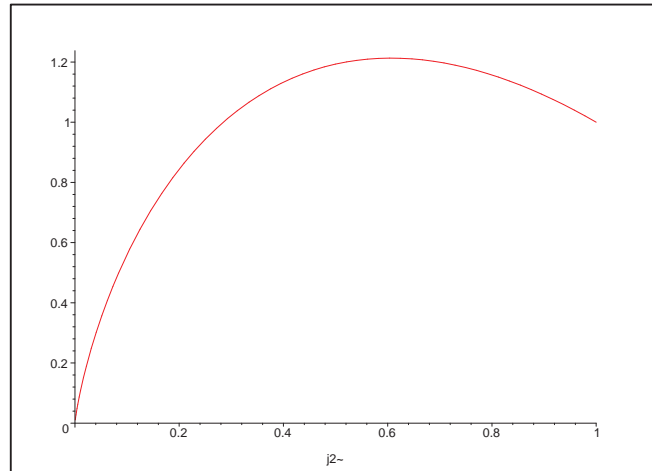


Figure 1:  $\varphi_2(j_2)$



We must now compute  $j_1$ . But we note that the first record can occur *after*  $j_2^*$ . It is clear from the unimodality of  $\varphi(j_2)$ , that  $j_2(u_1)$  is then exactly given by  $u_1$ . Actually

- $j_2(u_1) = j_2^*$  if  $u_1 < j_2^*$ ,
- $j_2(u_1) = u_1$  if  $u_1 \geq j_2^*$ .

So we obtain the following success probability  $P(j_1) = P_1(j_1) + P_2(j_1)$ , with, on the one hand

$$\begin{aligned} u_1 < j_2^* : P_1(j_1) &= \sum_{u_1=j_1}^{j_2^*-1} \prod_{i=j_1}^{u_1-1} \left(1 - \frac{1}{i}\right) \frac{1}{u_1} u_1 [F_1(u_1, j_2^*) + F_2(u_1, j_2^*)] \\ &= \sum_{u_1=j_1}^{j_2^*-1} \frac{j_1 - 1}{u_1 - 1} [F_1(u_1, j_2^*) + F_2(u_1, j_2^*)], \text{ which is unimodal in } j_1, \end{aligned} \quad (2)$$

and on the the other hand

$$\begin{aligned} j_2^* \leq u_1 < u_2 : P_2(j_1) &= \sum_{u_1=j_2^*}^{n-1} \sum_{u_2=u_1+1}^n \prod_{i=j_1}^{u_1-1} \left(1 - \frac{1}{i}\right) \frac{1}{u_1} \prod_{\ell=u_1+1}^{u_2-1} \left(1 - \frac{2}{\ell}\right) \frac{2}{u_2} \prod_{s=u_2+1}^n \left(1 - \frac{2}{s}\right) \\ &= \sum_{u_1=j_2^*}^{n-1} \sum_{u_2=u_1+1}^n \frac{2}{u_2 - 2} \frac{j_1 - 1}{n} \frac{1}{n - 1}, \text{ which is again monotone in } j_1. \end{aligned} \quad (3)$$

Therefore  $P(j_1) = P_1(j_1) + P_2(j_1)$  is unimodal in  $j_1$ . This gives the final asymptotic success probability, namely

$$\begin{aligned} V_2(j_1) &= j_1 \int_{j_1}^{j_2^*} \frac{1}{u_1} V_1(u_1, j_2^*) du_1 + j_1 \int_{u_1=j_2^*}^1 \int_{u_2=u_1}^1 \frac{2}{u_2} du_2 du_1 \\ &= j_1 [j_1 - 2 \ln(j_1) e^{-1/2} - 5e^{-1/2} + 2]. \end{aligned}$$

Maximizing  $V_2(j_1)$  then yields the asymptotically optimal threshold

$$j_1^* = -e^{-1/2} W(-\exp(-3 + e^{1/2})) = 0.2291147286 \dots$$

where  $W(x)$  is the Lambert function, that is the solution of

$$W(x)e^{W(x)} = x.$$

We use its principal branch which is analytic at 0. This leads from the above to  $V_2(j_1^*) = 0.2254366561 \dots$  and the value  $j_1^*$  is unique since  $V_2(j_1)$  is unimodal in  $j_1$ . A plot of  $V_2(j_1)$  is given in Figure 2.

We have compared, for  $n = 500$ ,  $V_2(j_1)$  with  $P(j_1)$ . This is shown in Figure 3 (line= $V_2(j_1)$ , box= $P(j_1)$ ). This is quite satisfactory. The relative error at  $j_1^*$  is given by  $\frac{V_2(j_1^*)}{P(j_1^*)} - 1 = -0.0033478319 \dots$

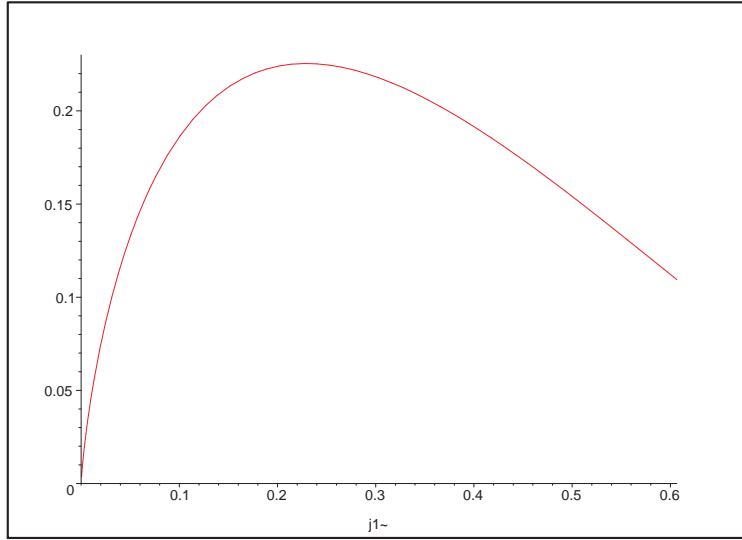


Figure 2:  $V_2(j_1)$

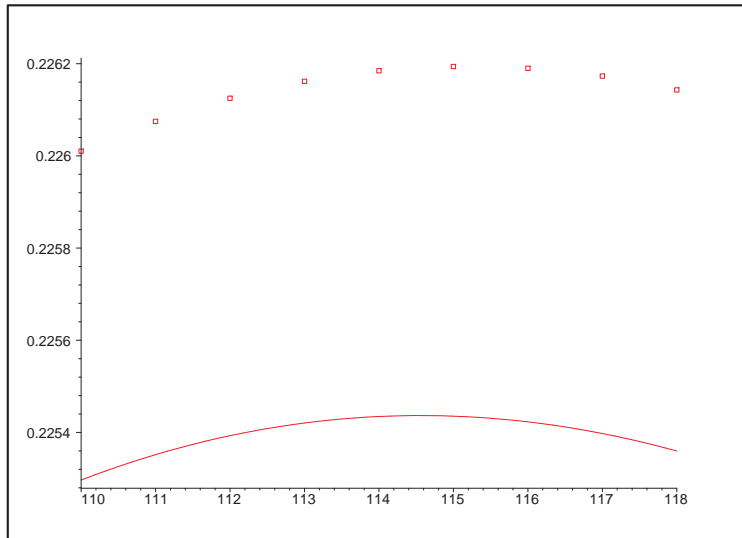


Figure 3: Comparison, for  $n = 500$  of  $V_2(j_1)$  (line) with  $P(j_1)$  (box).

### 3 The case $\kappa = 3$

The strategy for general  $\kappa$  proceeds as follows. Assume that we are at time  $u \in [j_k^*, j_{k+1}^*)$ ,

- if we have already chosen  $k - 1$  candidates or less, we select a *marginal candidate* (if any) in  $[u, j_{k+1}^*)$ ;
- if we have already chosen more than  $k - 1$  candidates, we select a *compulsory candidate* (if any) in  $[u, j_{k+1}^*)$ .

The initial condition is the following: for  $u \in [j_1^*, j_2^*)$ , the *marginal candidate* is the first record, by definition.

Let us now consider the case  $\kappa = 3$ . We must first compute  $j_3(u_2) \geq u_2$ , given  $u_2$  (at this time, we have selected the second candidate). Again, we have two possibilities:  $u_2 < j_3 \leq u_3$ , or, alternatively,  $u_2 < u_3 < j_3$ . From now on, we will omit the  $G$ -function expressions.

The probability of success of the first case is given by

$$\begin{aligned} & \sum_{u_3=j_3}^n \prod_{s=u_2+1}^{j_3-1} \left(1 - \frac{2}{s}\right) \prod_{t=j_3}^{u_3-1} \left(1 - \frac{3}{t}\right) \frac{3}{u_3} \prod_{v=u_3+1}^n \left(1 - \frac{3}{v}\right) \\ &= \sum_{u_3=j_3}^n \frac{3}{u_3 - 3} \prod_{s=u_2+1}^n \left(1 - \frac{2}{s}\right) \frac{j_3 - 3}{n - 2} =: \prod_{s=u_2+1}^n \left(1 - \frac{2}{s}\right) F_3(u_2, j_3) \text{ say,} \end{aligned}$$

Note that this expression is unimodal in  $j_3$  if and only if

$$g(j_3) := \frac{3}{n - 2} \sum_{u_3=j_3}^n \frac{1}{u_3 - 3} (j_3 - 3)$$

is unimodal in  $j_3$ . This is true if

$$h(j) := \left( \sum_{u=j}^n \frac{j - 3}{u - 3} \right) - \left( \sum_{u=j+1}^n \frac{(j - 3) + 1}{u - 3} \right)$$

changes, as a function of  $j$ , at most once its sign. An easy calculation shows that

$$h(j) = 1 - \sum_{u=j+1}^n \frac{1}{u - 3}$$

so that  $h(j)$  is monotone increasing in  $j$ .

The probability of success of the second case is given by

$$\sum_{u_3=u_2+1}^{j_3-1} \prod_{s=u_2+1}^{u_3-1} \left(1 - \frac{2}{s}\right) \frac{2}{u_3} \prod_{t=u_3+1}^n \left(1 - \frac{3}{t}\right)$$

$$= \sum_{u_3=u_2+1}^{j_3-1} \frac{2}{n-2} \prod_{s=u_2+1}^n \left(1 - \frac{2}{s}\right) =: \prod_{s=u_2+1}^n \left(1 - \frac{2}{s}\right) F_4(u_2, j_3) \text{ say,}$$

which is clearly monotone in  $j_3$ . Asymptotically, from  $F_3(u_2, j_3) + F_4(u_2, j_3)$ , conditioning on  $u_2$ , we must maximize, with respect to the index  $j_3$ , the function

$$V_3(u_2, j_3) := \int_{j_3}^1 3 \frac{j_3}{u_3} du_3 + \int_{u_2}^{j_3} 2 du_3 = -2u_2 + 2j_3 - 3j_3 \ln(j_3).$$

Note the similarity with  $V_1$  given in equation (1). This gives  $j_3^* = e^{-1/3} = .7165313106\dots$ . Again we note that  $V_3(u_2, j_3)$  has the form  $\varphi_3(u_2) + \varphi_4(j_3)$ , and that  $\varphi_4(j_3)$  is unimodal in  $j_3$ .

We must now compute  $j_2(u_1) \geq u_1$  given  $u_1$ . But we note that the relevant position  $u_2$  can occur *after*  $j_3^*$ . It is then clear, from the unimodality of  $\varphi_4(j_3)$ , that  $j_3(u_2)$  is then exactly given by  $u_2$ . Actually,

- $j_3(u_2) = j_3^*, u_2 < j_3^*$ ,
- $j_3(u_2) = u_2, u_2 \geq j_3^*$ .

We have now to consider the following cases:

- $u_1 < j_2 \leq u_2 < j_3^*$ ,
- $u_1 < j_2 < j_3^* < u_2 < u_3$ ,
- $u_1 < u_2 \leq j_2 < j_3^*$ .

This leads respectively to

$$\begin{aligned} P_3(u_1, j_2) &= \sum_{u_2=j_2}^{j_3^*-1} \prod_{k=u_1+1}^{j_2-1} \left(1 - \frac{1}{k}\right) \prod_{\ell=j_2}^{u_2-1} \left(1 - \frac{2}{\ell}\right) \frac{2}{u_2} \prod_{s=u_2+1}^n \left(1 - \frac{2}{s}\right) [F_3(u_2, j_3^*) + F_4(u_2, j_3^*)] \\ &= \sum_{u_2=j_2}^{j_3^*-1} \frac{2}{u_2 - 2} \frac{u_1}{n} \frac{j_2 - 2}{n - 1} [F_3(u_2, j_3^*) + F_4(u_2, j_3^*)], \end{aligned}$$

Note the similarity with equation (2),

$$\begin{aligned} P_4(u_1, j_2) &= \sum_{u_2=j_3^*}^{n-1} \sum_{u_3=u_2+1}^n \prod_{k=u_1+1}^{j_2-1} \left(1 - \frac{1}{k}\right) \prod_{\ell=j_2}^{u_2-1} \left(1 - \frac{2}{\ell}\right) \frac{2}{u_2} \prod_{s=u_2+1}^{u_3-1} \left(1 - \frac{3}{s}\right) \frac{3}{u_3} \prod_{t=u_3+1}^n \left(1 - \frac{3}{t}\right) \\ &= \sum_{u_2=j_3^*}^{n-1} \sum_{u_3=u_2+1}^n \frac{6}{u_3 - 3} \frac{u_1}{n} \frac{j_2 - 2}{(n-1)(n-2)}, \end{aligned}$$

Note the similarity with equation (3),

$$\begin{aligned}
P_5(u_1, j_2) &= \sum_{u_2=u_1+1}^{j_2-1} \prod_{k=u_1+1}^{u_2-1} \left(1 - \frac{1}{k}\right) \frac{1}{u_2} \prod_{s=u_2+1}^n \left(1 - \frac{2}{s}\right) [F_3(u_2, j_3^*) + F_4(u_2, j_3^*)] \\
&= \sum_{u_2=u_1+1}^{j_2-1} \frac{u_1}{n(n-1)} [F_3(u_2, j_3^*) + F_4(u_2, j_3^*)].
\end{aligned}$$

Asymptotically, conditioning on  $u_1$ , we must then maximize

$$\begin{aligned}
V_4(u_1, j_2) &= \int_{j_2}^{j_3^*} 2 \frac{j_2}{u_2} V_3(u_2, j_3^*) du_2 + \int_{u_2=j_3^*}^1 \int_{u_3=u_2}^1 6 \frac{j_2}{u_3} du_3 du_2 + \int_{u_1}^{j_2} V_3(u_2, j_3^*) du_2 \\
&= -3e^{-1/3} u_1 + u_1^2 + 3j_2^2 + 6j_2 - 6e^{-1/3} j_2 \ln(j_2) - 11j_2 e^{-1/3}.
\end{aligned}$$

This gives  $j_2^* = -e^{-1/3} W(-\exp(-5/2 + e^{1/3})) = .4369818602\dots$ . Again we note that  $V_4(u_1, j_2)$  has the form  $\varphi_5(u_1) + \varphi_6(j_2)$  and  $\varphi_6(j_2)$  is unimodal in  $j_2$ .

We now compute  $j_1$ . We note that  $u_1$  can occur *after*  $j_2^*$ . It is then clear, from the unimodality of  $\varphi_6(j_2)$ , that  $j_2(u_1)$  is then exactly given by  $u_1$ . Actually now the split in the index  $j_2^*$  is given by

- $j_2(u_1) = j_2^*, u_1 < j_2^*$ ,
- $j_2(u_1) = u_1, u_1 \geq j_2^*$ .

We obviously need a concise notation for all cases we will consider (this will of course be applied to cases  $\kappa \geq 4$ ). This is related with the Bose-Einstein statistic, where, here, we throw  $\kappa$  indistinguishable balls into  $\kappa$  ordered urns labelled  $1, 2, \dots, \kappa$ . The number of possible cases is given by  $\binom{2\kappa-1}{\kappa}$  i.e. 10 cases for  $\kappa = 3$ . We next label the balls in increasing order. Denote then by  $(\alpha_1, \alpha_2, \alpha_3)$  the urn labels of balls  $(1, 2, 3)$ . In our model, balls correspond to chosen candidates and urns to intervals  $[j_k, j_{k+1} - 1]$ . For instance, the case  $(1, 3, 3)$  corresponds to  $j_1 \leq u_1 < j_2^* < j_3^* \leq u_2 < u_3$  and the corresponding probability is given by

$$\begin{aligned}
&\sum_{u_1=j_1}^{j_2^*-1} \sum_{u_2=j_3^*}^{n-1} \sum_{u_3=u_2+1}^n \prod_{i=j_1}^{u_1-1} \left(1 - \frac{1}{i}\right) \frac{1}{u_1} \prod_{k=u_1+1}^{j_2^*-1} \left(1 - \frac{1}{k}\right) \prod_{\ell=j_2^*}^{u_2-1} \left(1 - \frac{2}{\ell}\right) \frac{2}{u_2} \times \\
&\times \prod_{s=u_2+1}^{u_3-1} \left(1 - \frac{3}{s}\right) \frac{3}{u_3} \prod_{t=u_3+1}^n \left(1 - \frac{3}{t}\right).
\end{aligned}$$

We will not detail the tedious, but routine computations corresponding to our 10 cases. We provide only the final asymptotic integrals.

For this we must maximize the success probability  $V_5(j_1) = j_1[K_1 + K_2 + K_3 + K_4 + K_5]$  with

cases  $(1, 1, 1), (1, 1, 2), (1, 1, 3), (1, 2, 2), (1, 2, 3), (1, 3, 3)$  :

$$K_1 = \int_{j_1}^{j_2^*} \frac{1}{u_1} V_4(u_1, j_2^*) du_1,$$

case (2, 2, 3) :

$$K_2 = \int_{u_1=j_2^*}^{j_3^*} \int_{u_2=u_1}^{j_3^*} \int_{u_3=j_3^*}^1 6 \frac{j_3^*}{u_2 u_3} du_3 du_2 du_1,$$

case (2, 3, 3) :

$$K_3 = \int_{u_1=j_2^*}^{j_3^*} \int_{u_2=j_3^*}^1 \int_{u_3=u_2}^1 6 \frac{1}{u_3} du_3 du_2 du_1,$$

case (2, 2, 2) :

$$K_4 = \int_{u_1=j_2^*}^{j_3^*} \int_{u_2=u_1}^{j_3^*} \int_{u_3=u_2}^{j_3^*} 4 \frac{1}{u_2} du_3 du_2 du_1,$$

case (3, 3, 3) :

$$K_5 = \int_{u_1=j_3^*}^1 \int_{u_2=u_1}^1 \int_{u_3=u_2}^1 6 \frac{1}{u_3} du_3 du_2 du_1.$$

Maximizing  $V_5(j_1)$  leads to an equation of type

$$C_1 j_1^2 + C_2 j_1 + C_3 \ln(j_1) + C_4 = 0,$$

where  $C_i$  depends on  $j_2^*, j_3^*$ . This equation does not have an explicit solution.

But if we introduce a “generalized” Lambert function  $W_1(x, y)$  as being defined by

$$W_1 e^{y W_1 + W_1^2} = x,$$

we can express  $j_1^*$  as

$$\begin{aligned} j_1^* &= W_1(x, y), \\ x &= e^{-C_4/C_3} / C_5, \\ y &= C_2 C_5 / C_3, \\ C_5 &= \sqrt{C_3 / C_1}. \end{aligned}$$

Numerically, this gives  $j_1^* = .1666171752 \dots$  and the success probability  $V_5(j_1^*) = .1625200069 \dots$ . Again,  $V_5(j_1)$  is unimodal in  $j_1$  as well as all relevant discrete expressions in this section.

We note that the easier problem of predicting an index from which onwards we have exactly three record values has an optimal value of  $0.224042 \dots$ . See Bruss and Paindaveine [4], Sec. 6, equation (13):

$$V(\ell) = \frac{\ell^\ell}{\ell! e^\ell},$$

$$\ell = 3 : V(3) = \frac{9}{2}e^{-3} = 0.22404 \dots$$

Hence, getting the three very best is actually not so much harder, and this came somewhat as a surprise to us.

## 4 Conclusion

It is in the nature of the problem that even only asymptotic answers are computationally involved. Still, using similar simple probabilistic arguments, we can compute a set of asymptotic thresholds and the final success probability for any  $\kappa$ . Further work would be to build a computer algebra system which could mechanically compute the different cases and the corresponding asymptotic probabilities. This computer algebra should bring the relevant involved functions in a sufficient tractable form to prove the unimodality for all  $\kappa$  in the asymptotic continuous case? This would be all we need to prove asymptotic optimality also for the case  $\kappa \geq 4$ . Hence there remain two interesting open problems:

## 5 Open problems

PROBLEM 1: Is our procedure for finding the  $\kappa$  best secretaries out of  $n$  candidates optimal for all  $\kappa$ ?

PROBLEM 2: Can this procedure be extended to the case where  $\kappa$  depends on  $n$ ?

## References

- [1] K. Ano, H. Kakinuma, and N. Miyoshi. Odds theorem with multiple selection chances. *Journal of Applied Probability*, 47(4):1093–1104, 2010.
- [2] F.T. Bruss. Sum the odds to one and stop. *Annals of Probability*, 28(3):1384–1391, 2000.
- [3] F.T. Bruss. A note on the odds-theorem of optimal stopping. *Annals of Probability*, 31(4):1859–1861, 2003.
- [4] F.T. Bruss and D. Paindaveine. Selecting a sequence of last successes in independent trials. *Journal of Applied Probability*, 37(2):389–399, 2000.
- [5] Y.S. Chow, S. Moriguti, H. Robbins, and S.M. Samuels. Optimal selection based on relative rank. *Israel Journal of mathematics*, 2(2):81–90, 1964.

- [6] R. Dendievel. New developments of the odds-theorem. *Mathematical Scientist*, 38:111–123, 2013.
- [7] T.S. Ferguson. Who solved the secretary problem? *Statistical Science*, 4(3):282–289, 1989.
- [8] D.V. Lindley. Dynamic programming and decision theory. *Applied Statistics*, 10:35–51, 1961.
- [9] H. Platen. About secretary problems. *Mathematical Statistics, Banach Center Publications*, 6:257–266, 1980.
- [10] J.S. Rose. A problem of optimal choice and assignment. *Operations Research*, 30:172–181, 1982.
- [11] K. Szajowski and D. Lebek. Optimal strategies in high risk investments. *Bulletin of the Belgian Mathematical Society*, 14(1):143–155, 2007.
- [12] M. Tamaki. The secretary problem with optimal assignments. *Operations Research*, 32:847–858, 1984.
- [13] R. J. Vanderbei. The optimal choice of a subset of a population. *Mathematics of Operations Research*, 5(4):481–487, 1980.
- [14] R.J. Vanderbei. The postdoc variant of the secretary problem. Technical report, Princeton University.
- [15] J.G. Wilson. Optimal choice and assignment of the best  $m$  of  $n$  randomly arriving items. *Stochastic Processes and Their Applications*, 39:325–343, 1991.