CONFIDENCE BOUNDS FOR THE MEAN IN NONPARAMETRIC MULTISAMPLE PROBLEMS

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Confidence bounds for the mean in nonparametric multisample problems

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Abstract

In auditing practice it often occurs that a statement regarding the accounting error in a population consisting of several subpopulations has to be made. Since the relative proportion of errors can differ dramatically across these subpopulations, it is desirable to take independent fixed size dollar-unit samples from each of them, as this often leads to lower variability compared to dollar-unit sampling from the whole population. It also occurs that the results of the separate investigations of, e.g., different branches of one company need to be combined to make a statement on the bookkeeping quality in general.

The problem of estimating the total accounting error is thus related to the problem of estimating linear combinations of the means corresponding to several families of identically distributed independent random variables.

In this article, we propose several confidence upper bounds for such linear combinations based on Hoeffding type inequalities and show how they can be applied in the actual auditing problems. Simulation results comparing these modifications to the Hoeffding-based bounds for the one-sample case are also provided. It must be emphasized that the technique that we propose in this paper is fully justified from a mathematical point of view.

Although the simulations show the proposed bounds to be highly conservative, they still present great interest, since we are not aware of any other method for estimation of the total accounting error in the multisample setting. Moreover, it is shown that significant improvements are hardly possible given the present conditions.

Keywords— bookkeeping quality, lower and upper confidence bounds and intervals, conservativeness, auditing, Hoeffding inequalities, finite populations, multisample problems, computer simulations, Stringer bound.

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1 Introduction

An important problem in the world of statistical auditing is the so-called multi-sample problem. In auditing practice it often occurs that the auditor has to make a statement concerning the total error in a population of dollars, which consists of several individually sampled subpopulations. For example, it is often needed to obtain a combined confidence upper bound from the sample results in the individual subpopulations (without using, for instance, a Bonferroni type of inequality, as the latter technique would generally lead to bad confidence upper bounds). It also happens that a company is comprised of several branches, and the results of quantitative analysis indicate that there is a significant difference in the bookkeeping quality between them. In this case, random sampling without accounting for this difference is going to result in the unwanted increase of the variability in the sample.

In this section we are going to discuss this combination problem in the two-sample setting.

Suppose that a population $A$ of $N = K + L$ monetary items is a union $A = B \cup C$ of two subpopulations $B$ and $C$ that contain respectively $K$ and $L$ items with book values $B_1, B_2, \ldots, B_K$, and $C_1, C_2, \ldots, C_L$.

Let the errors which are hidden in these book values be respectively $E_1^B, E_2^B, \ldots, E_K^B$ and $E_1^C, E_2^C, \ldots, E_L^C$.

We assume that only overstatement errors are present, that is $0 < E_i^B < B_i$ and $0 < E_j^C < C_j$ for all possible values of $i$ and $j$.

Then the total book values of the subpopulations are respectively $B = B_1 + B_2 + \cdots + B_K$ and $C = C_1 + C_2 + \cdots + C_L$,

and the total errors hidden in $B$ and $C$ are given by

$E^B = E_1^B + E_2^B + \cdots + E_K^B$ and $E^C = E_1^C + E_2^C + \cdots + E_L^C$.

Therefore, the book value and the combined error in the total population $A$ can be written as

$A = B + C$ and $E = E^B + E^C$.

As usual, the tainting associated with the accounts in the subpopulations $B$ and $C$ are defined as

$t_i^B = \frac{E_i^B}{B_i}$ and $t_j^C = \frac{E_j^C}{C_j}$

for all possible values of $i$ and $j$. 
Finally, the relative book values of the subpopulation and the relative errors are

$$\alpha_1 = \frac{B}{A}, \quad \alpha_2 = \frac{C}{A}$$

and

$$\mu_1 = \frac{E^B}{B}, \quad \mu_2 = \frac{E^C}{C}$$

respectively. Then for the proportion of errors in the whole population defined as

$$\mu = \frac{E}{A}$$

we have

$$\mu := \alpha_1 \mu_1 + \alpha_2 \mu_2. \quad (1.1)$$

In order to derive a confidence upper bound for the total error $E$ or equivalently for $\mu$, we take independent samples from the subpopulations B and C. Using the dollar-unit sampling technique as described in Bickel (1992) we draw (with replacement) $k$ independent taintings (relative errors) from the population B and $l$ taintings from the population C. This leads us to the total of $n = k + l$ independent samples

$$U_1, U_2, \ldots, U_k \quad \text{and} \quad V_1, V_2, \ldots, V_l,$$

where

$$\mathbb{P}(U_s = t^B_i) = \frac{B_i}{B} \quad \text{and} \quad \mathbb{P}(V_t = t^C_j) = \frac{C_j}{C}$$

for all possible values of $s$, $t$, $i$ and $j$.

The sample means will be written as

$$\bar{U} = \frac{U_1 + U_2 + \cdots + U_k}{k} \quad \text{and} \quad \bar{V} = \frac{V_1 + V_2 + \cdots + V_l}{l}.$$

For all $s = 1, 2, \ldots, k$ and $t = 1, 2, \ldots, l$ we clearly have

$$\mathbb{E}U_s = \frac{E^B}{B} = \mu_1 \quad \text{and} \quad \mathbb{E}V_t = \frac{E^C}{C} = \mu_2.$$

An important special case is the situation where the sample sizes are proportional to the population sizes, i.e.

$$\frac{k}{n} = \alpha_1 \quad \text{and} \quad \frac{l}{n} = \alpha_2. \quad (1.2)$$

Our results are based on the relationship between upper confidence bounds for a parameter and upper bounds for the tail probabilities depending on this parameter, as described in the appendix. In the nonparametric one-sample setting, the best known estimates for the tail probabilities come from Hoeffding inequalities. A direct adaptation of these results to the two-sample auditing problem is possible, and is described in section 2. However, the efficiency of this approach leaves much to be
desired, requiring extensions of Hoeffding’s theorems. Despite considerable analytical difficulties, such an extension has been proved. It is presented in section 3, followed by a construction of a more efficient bound incorporating prior information.

In the end of sections 2 and 3 the applications of our results to the auditing problem are clarified, and computer simulation results are presented in section 4.

The appendix also contains the proof of the inequality leading to the improvement of Hoeffding’s results mentioned above.

2 A confidence upper bound for the total auditing error in two populations

Let $S_1, S_2, \ldots, S_k$ and $T_1, T_2, \ldots, T_l$ be independent random variables, where $k$ and $l$ are positive integers, $k + l = n$. We further assume that the random variables $S_1, S_2, \ldots, S_k$ are identically distributed according to the distribution function $F_1^*$, and that the same holds for $T_1, T_2, \ldots, T_l$ with the corresponding distribution function $F_2^*$.

In the auditing context we can assume without loss of generality that the values of $S_i$ and $T_j$ are in the interval $[0, 1]$, hence

$$P(0 \leq S_i \leq 1) = 1 \quad \text{and} \quad P(0 \leq T_j \leq 1) = 1.$$ 

Denote the expectations and the variances of these random variables by

$$\lambda_1 = \mathbb{E}S_i \quad \text{and} \quad \eta_1^2 = \text{Var}(S_i); \quad \lambda_2 = \mathbb{E}T_j \quad \text{and} \quad \eta_2^2 = \text{Var}(T_j)$$

respectively. Consider the sample means

$$\bar{S} = \frac{S_1 + \ldots + S_k}{k}, \quad \bar{T} = \frac{T_1 + \ldots + T_l}{l},$$

and

$$\bar{S} \cup \bar{T} = \frac{S_1 + \ldots + S_k + T_1 + \ldots + T_l}{n}.$$ 

Clearly, we have

$$\mathbb{E}\bar{S} = \lambda_1, \quad \mathbb{E}\bar{T} = \lambda_2 \quad \text{and} \quad \mathbb{E}\bar{S} \cup \bar{T} = \lambda,$$

where

$$\lambda = \frac{k}{n} \lambda_1 + \frac{l}{n} \lambda_2.$$ 

Let $H(a; \nu)$, $0 \leq \nu \leq 1$, be the Hoeffding function, which is defined as

$$H(a; \nu) = \left(1 - \frac{\nu}{1 - a}\right)^{1-a} \left(\frac{\nu}{a}\right)^a \quad \text{for} \quad \nu < a \leq 1$$

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and \( H(a; \nu) = 1 \) for \( a \leq \nu \); \( H(a; \nu) = 0 \) for \( a > 1 \). The simplest Hoeffding inequality can be formulated as follows.

**Lemma 1.** Assuming that random variables \( S_i \) and \( T_j \) satisfy the conditions given above, the following inequality holds for \( x \in [0, 1] \)

\[
P \left( \frac{S}{\bar{S}} \geq x \right) \leq P \left( 1 - \frac{S}{\bar{S}} \geq 1 - x \right) \leq H^n(1 - x, 1 - \lambda). \tag{2.1}
\]

**Proof of Lemma 1.** Lemma 1 is a simple corollary of Th.1 in Hoeffding (1963). □

Let us construct a confidence upper bound for \( \lambda \) based on this inequality. For \( \alpha \in (0, 1), x \in [0, 1] \) and \( n \in \mathbb{N} \) write

\[
b_1(x) = \max \left\{ \mu : 0 \leq \mu \leq 1 \text{ and } H(1 - x, 1 - \mu) \geq \alpha^{1/n} \right\}. \tag{2.2}
\]

**Statement 1.** The statistic \( b_1(\bar{S} \| \bar{T}) \) is a \((1 - \alpha)\)-confidence upper bound for \( \lambda \), i.e.

\[
P \left( \lambda \leq b_1(\bar{S} \| \bar{T}) \right) \geq 1 - \alpha.
\]

**Proof of Statement 1.** This statement can be easily derived from Lemma 1 using the methods described in Bentkus and van Zuijlen (2003). A more general description of this methodology can be found in Bentkus et al. (2001) and Finkelstein et al. (2000). Note that this bound is, in fact, the bound \( b_1 \) by Bentkus and van Zuijlen (2003), which has been rewritten for the two-sample case. □

Going back to the auditing setup presented in the introduction, consider the random variables

\[
U_1, U_2, \ldots, U_k, \text{ and } V_1, V_2, \ldots, V_l.
\]

It is easy to see that in the case of proportional sampling as defined by (1.2) we have

\[
\frac{k}{n} \mu_1 + \frac{l}{n} \mu_2 = \mu,
\]

and hence the statistic

\[
A_{b1}(\bar{U} \| \bar{V})
\]

is a \((1 - \alpha)\)-confidence upper bound for \( E \).

Statement 1 can be generalized for the non-proportional case in the following way. Write

\[
c_1 = \frac{n}{k} \omega_1, \quad c_2 = \frac{n}{l} \omega_2, \quad c = \max \{c_1, c_2\}. \tag{2.3}
\]

Random variables defined as

\[
U'_i = \frac{c_1}{c} U_i, i = 1, 2, \ldots, k, \quad V'_j = \frac{c_2}{c} V_j, j = 1, 2, \ldots, l
\]
satisfy the probability inequalities $\mathbb{P}(0 \leq U' \leq 1) = 1$ and $\mathbb{P}(0 \leq V_2^* \leq 1) = 1$. According to Statement 1, the statistic $b_1(U' \cup V')$ is a $(1 - \alpha)$-confidence upper bound for the value

$$
\mu' = E(U' \cup V') = \frac{k}{n} \frac{c_1}{c} \mu_1 + \frac{l}{n} \frac{c_2}{c} \mu_2 = \frac{\alpha_1 \mu_1 + \alpha_2 \mu_2}{c} = \frac{\mu}{c}.
$$

**Corollary 1.** Let $U_1, \ldots, U_k$ and $V_1, \ldots, V_l$ be dollar-unit tainting samples taken from populations $B$ and $C$ respectively. Then the statistic

$$
A \cdot c \cdot b_1 \left( \frac{c_1 U + c_2 V}{c} \right)
$$

is a $(1 - \alpha)$-confidence upper bound for the total error $E$.

**Proof of Corollary 1.** By the argument above, the statistic

$$
b_1(U' \cup V') = b_1 \left( \frac{c_1 U + c_2 V}{c} \right)
$$

is a $(1 - \alpha)$-confidence upper bound for $\mu/c$. This, together with (1.1), proves the corollary.

\[ \square \]

It is clear that, in general, larger values of $c$ will correspond to more conservative upper bounds for $E$. Therefore, for practical applications it is advised to choose $k$ and $l$ in such a way that $c$ is minimal.

## 3 A confidence upper bound for the total auditing error in two populations based on a modification of the second Hoeffding inequality

Under the assumptions made in Section 2, let us consider the case where some apriori information is available in the form $\lambda_1 \leq \lambda_1^{(0)}, \lambda_2 \leq \lambda_2^{(0)}, \eta_1 \leq \eta_1^{(0)}, \eta_2 \leq \eta_2^{(0)}$.

As in the previous section, we define $c_1 = \alpha_1(n/k)$, $c_2 = \alpha_2(n/l)$. Write

$$
X_i = c_1 S_i, \quad Y_i = c_2 T_i, \quad (3.1)
$$

The mean values and the variances of $X_i$ and $Y_i$ are respectively

$$
\mu_1 = \lambda_1 c_1, \quad \mu_2 = \lambda_2 c_2, \quad \sigma_1^2 = \eta_1^{(0)} c_1^2, \quad \sigma_2^2 = \eta_2^{(0)} c_2^2.
$$

We also have $\mathbb{P}(0 \leq X_i \leq c_1) = 1$, $\mathbb{P}(0 \leq Y_i \leq c_2) = 1$.

Let $\mu$ be defined by

$$
\mu = \frac{k}{n} \mu_1 + \frac{l}{n} \mu_2.
$$
The bounds below are given for the case where $\mu < 1/2$. Since the proportion of errors in the populations investigated by auditors is typically quite low, this assumption hardly leads to any loss of generality in the auditing context.

For the statistic
\[ X \cup Y = \frac{X_1 + \ldots + X_k + Y_1 + \ldots + Y_l}{n} \]
we have $E(X \cup Y) = \frac{k}{n} \mu_1 + \frac{l}{n} \mu_2 = \mu$. Note that this is essentially a reduction of the problem to the case of proportional sampling as defined by (1.2).

In order to prove an analogue of the second Hoeffding inequality for the two-sample case, we are going to need the following result.

**Lemma 2.** Let $s$ be a real number, and let
\[ f(b, \sigma^2, h) = \ln \left( \frac{b^2}{b^2 + \sigma^2 e^{-(\sigma^2/\sigma b)}} + \frac{\sigma^2}{b^2 + \sigma^2 e^{hb}} \right). \]
Then for all positive real numbers $b_1, b_2, \sigma_1, \sigma_2$ and $h$ the inequality
\[ kf(b_1, \sigma_1^2, h) + lf(b_2, \sigma_2^2, h) \leq nf \left( \frac{k b_1 + l b_2}{n}, \frac{k}{n} \sigma_1^2 + \frac{l}{n} \sigma_2^2 + \frac{s + 1}{2} \frac{k}{n} \frac{l}{n} (b_1 - b_2)^2, h \right) \]
holds for $s \geq 0$, and for any real $s < 0$ there exists a combination of parameters $b_1, b_2, \sigma_1, \sigma_2$, $h$ such that the opposite inequality holds.

**Remark.** The heuristic considerations presented later in this article quickly led to the formulation of (3.2) with $s = 1$ as a conjecture, which was subsequently confirmed by computer simulations. However, an analytical proof, which can be found in the appendix, was not at all easy to obtain due to the complex form of the underlying function. Also, it must be noted that Lemmas 2 and 3, as well as the corresponding upper confidence bound, allow for a natural extension to the general multisample case.

**Lemma 3.** Let random variables $X_i$ and $Y_j$ be defined by (3.1). The following inequality holds for $t > 0$:
\[ \mathbb{P}(X \cup Y \leq \mu + t) \leq \left( 1 + \frac{b t}{\sigma^2} \right)^{-(1+bt/\sigma^2)/(\sigma^2+\sigma^2)} \left( 1 - \frac{t}{b} \right)^{-(1-t/b)/(\sigma^2+\sigma^2)} \]
where
\[ b_1 = c_1 - \mu_1, \ b_2 = c_2 - \mu_2, \ b = (k/n)(c_1 - \mu_1) + (l/n)(c_2 - \mu_2) \]
and
\[ \sigma^2 = \frac{k}{n} \sigma_1^2 + \frac{l}{n} \sigma_2^2 + \frac{k}{n} \frac{l}{n} (b_1 - b_2)^2. \]
Proof of Lemma 3. Consider the random variables \( X_i - \mu_1 \) and \( Y_j - \mu_2 \). Their expectations are equal to 0, and they are bounded from above by \( b_1 \) and \( b_2 \) respectively. By applying (1.7), (1.8) and Lemma 2 from Hoeffding (1963), we obtain for \( h > 0 \)

\[
P(\bar{X} \cup \bar{Y} \leq \mu + t) \leq e^{-hnt + kf(b_1, \sigma^2_1, h) + mf(b_2, \sigma^2_2, h)}
\]

(3.5)

Then, by Lemma 2,

\[
P(\bar{X} \cup \bar{Y} \leq \mu + t) \leq e^{-hnt + nf(\frac{b_1 + mb_2}{n}, \xi \sigma^2_1 + \frac{1}{n}(b_1 - b_2)^2, h)}
\]

(3.6)

The right-hand side of (3.6) attains its minimum at

\[
h = \frac{b}{b^2 + \sigma^2} \ln \left(\frac{1 + tb/j^2}{1 - t/b}\right).
\]

By inserting this value in (3.6) we obtain (3.3). \( \square \)

Remark. The modifications in the right hand side of (3.2) compared to inequality (2.8) in Hoeffding (1963) originate from the following intuitive argument. Let \( \tilde{X}_i, i = 1, 2, \ldots, n \) and \( \tilde{Y}_j, j = 1, 2, \ldots, n \) be independent random variables such that all \( \tilde{X}_i \) and \( \tilde{Y}_j \) are distributed identically to \( S_1 \) and \( T_1 \) respectively. Let \( \xi_k, k = 1, 2, \ldots, n \), be i.i.d. random Bernoulli variables such that \( P(\xi_k = 1) = \alpha_1 \), \( P(\xi_k = 0) = \alpha_2 = 1 - \alpha_1 \) and let the random variables in the set

\[
\{\tilde{X}_i, i = 1, 2, \ldots, n\} \cup \{\tilde{Y}_j, j = 1, 2, \ldots, n\} \cup \{\xi_k, k = 1, 2, \ldots, n\}
\]

be independent.

Write \( Z_i = \xi_i \tilde{X}_i + (1 - \xi_i) \tilde{Y}_i, i = 1, 2, \ldots, n \). These \( Z_i \) are i.i.d. random variables, with the expected value \( E(Z_i) = \mu \) and the variance equal to \( \text{Var}(Z_i) = \alpha_1 \sigma^2_1 + \alpha_2 \sigma^2_2 + \alpha_1 \alpha_2 (\mu_1 - \mu_2)^2 \). This corresponds to a sampling procedure from \( \tilde{X} \) and \( \tilde{Y} \) where a random number of items from each population is included in the sample, following a binomial distribution with parameters \( n, \alpha_1 \) and \( \alpha_2 \). Let \( HB_1(\mu) \) be the Hoeffding-based upper estimate for the corresponding tail probability, i.e.

\[
P\left(\frac{Z_1 + \ldots + Z_n}{n} > \mu + t\right) \leq HB_1(\mu),
\]

where \( t \) is greater than zero. For \( t > 0 \) one would expect \( HB_1(\mu) \) to be also an upper estimate for the tail probability in the case of fixed size sampling, i.e.

\[
P\left(\frac{\tilde{X}_1 + \ldots + \tilde{X}_k + \tilde{Y}_1 + \ldots + \tilde{Y}_l}{n} > \mu + t\right) \leq HB_1(\mu),
\]

since this corresponds to a sampling procedure which is intuitively less random and also gives a lower variance for the relevant statistic when \( \mu_1 \neq \mu_2 \).
Lemma 2 is a generalization of theorem 3 in Hoeffding (1963). However, it doesn’t improve the corresponding inequalities for all possible combinations of the parameters $b_1$, $b_2$, $\sigma_1$, $\sigma_2$ and $t$. Instead, it is necessary to take the minimum over all valid combinations of $b_1$ and $b_2$ as given below.

**Corollary 2.** Let random variables $X_i$ and $Y_j$ be defined by (3.1). Let $b_1 = c_1 - \mu_1$, $b_2 = c_2 - \mu_2$. Without loss of generality we can assume that $b_1 \leq b_2$. The following inequality holds for $t > 0$:

$$
\mathbb{P}(X \cup Y \leq \mu + t) \leq \min_{b_1 \leq b'_1 \leq b_2} \left\{ \left(1 + \frac{bt}{\sigma^2}\right)\left(1 - \frac{t}{b}\right)\right\}^n,
$$

where $b = (k/n)b'_1 + (l/n)b_2$ and

$$
\sigma^2 = \frac{k}{n}\sigma_1^2 + \frac{l}{n}\sigma_2^2 + \frac{k}{n^2}(b'_1 - b_2)^2.
$$

**Proof of Corollary 2.** Taking $c'_i = b'_i + \mu'_i$ we have that $c'_i \geq c_1$ and therefore

$$
\mathbb{P}(0 \leq X_i \leq c'_i) = 1.
$$

The inequality (3.7) follows directly from (3.3) with $c_1$ substituted by $c'_1$. □

Now, by using the methods described in Bentkus and van Zuijlen (2003) it is possible to introduce a confidence upper bound for $\mu$ based on the inequality (3.7) that utilizes the available apriori information and also depends on the sample variances.

Let $b_1 = c_1 - \mu_1$, $b_2 = c_2 - \mu_2$. Let $\hat{\sigma}_1^2$ be the sample variance of $X_1, \ldots, X_k$. Given below are auxiliary functions needed to construct a certain confidence upper bound for a variance. For a detailed description of this bound refer to Bentkus and van Zuijlen (2003). Let

$$
t^B_3(\mu_1) = \left\{ \min \left\{ t : H(\tau(\mu_1) + 2t; \tau(\mu_1)) \leq \beta_1^{1/[k/2]} \right\}, \text{ if } \tau(\mu_1) \leq \beta_1^{1/[k/2]} ; \right\} \mu_1 - \mu'_1, \text{ otherwise,}
$$

$$
t^B_2 = t^B_2 \left( \lambda_1^{(0)} \right);
$$

$$
t^B_4 = \left\{ \min \left\{ t : H \left( \chi \left( \eta_1^{(0)} \right) + 2t; \chi \left( \eta_1^{(0)} \right) \right) \leq \beta_1^{1/[k/2]} \right\}, \text{ if } \chi \left( \eta_1^{(0)} \right) \leq \beta_1^{1/[k/2]} ; \right\} \left( \eta_1^{(0)} \right)_2, \text{ otherwise,}
$$

where $\tau(x) = 1 - 2x + 2x^2$, $\chi(x) = 1 - 2x^2$ and $\beta_1$ lies in the interval $(0, 1)$.

Finally, write

$$
t^B_5(\lambda_1) = \min \left\{ \left( \eta_1^{(0)} \right)_2, \mu_1 - \mu'_1, \hat{\sigma}_1^2, \text{ min } \{ t^B_2, t^B_3(\mu_1), t^B_4 \} \right\}.
$$
It is shown in Bentkus and van Zuijlen, (2003) that the bound $t_B(\lambda_1)$ is a confidence upper bound for the variance $\eta_1^2$ with risk $\beta_1$ given that $\eta_1 \leq \eta_1^{(3)}$. It is possible to define a bound $t_C(\lambda_2)$ for the variance $\eta_2^2$ with risk $\beta_2$ in the same way.

Write

$$t(\lambda_1, \lambda_2) = \left( \frac{k^2 c_1^2 t_B(\lambda_1)}{n} + \frac{l^2 c_2^2 t_C(\lambda_2)}{n} \right).$$

It is a confidence upper bound for the value $\frac{k}{n} \sigma_1^2 + \frac{l}{n} \sigma_2^2$ with risk $\beta_1 + \beta_2$.

For a given function $z : [0, 1/2) \times [0, 1/2) \to \mathbb{R}$, consider the functional

$$B(x, z(\cdot)) = \max \left\{ \rho = \frac{k}{n} c_1 \lambda_1 + \frac{l}{n} c_2 \lambda_2 : H_2 \left( 1 - \rho', x - \rho', z(\lambda_1, \lambda_2) + \frac{1}{2} \frac{k}{n} c_1 (1 - \lambda_1) + \frac{l}{n} c_2 (1 - \lambda_2) \right)^2 \geq (\alpha - \beta_1 - \beta_2)^{1/n} \right\},$$

(3.8)

where

$$H_2(b, t, \sigma) = \left( 1 + \frac{bt}{\sigma^2} \right)^{-\frac{1}{2} \frac{bt}{\sigma^2} / (b^2 + \sigma^2)} \left( 1 - \frac{b}{t} \right)^{-\frac{1}{2} \frac{bt}{\sigma^2} / (b^2 + \sigma^2)},$$

and $\lambda_1 \leq \lambda'_1 \leq \max\{\lambda_1, \lambda_2\}$, $\lambda_2 \leq \lambda'_2 \leq \max\{\lambda_1, \lambda_2\}$, $\rho' = \frac{k}{n} c_1 \lambda_1 + \frac{l}{n} c_2 \lambda_2$.

**Statement 3.** The statistic $b_2^\ast(X \cup \bar{Y})$ defined by

$$b_2^\ast(X \cup \bar{Y}) = B(X \cup \bar{Y}, t(\cdot))$$

(3.9)

is a confidence upper bound for $\mu$ with risk $\alpha$.

**Proof of Statement 3.** The proof can be easily obtained by using corollary 2 and applying the methods described in Bentkus and van Zuijlen (2003) for the bound $b_6$.

Returning to the original auditing problem, we can prove the following corollary.

**Corollary 3.** Assume that the auditor has been able to translate his judgement of the bookkeeping quality (which is based on his previous experience) into apriori upper estimates for the proportion of errors in each population, namely $\mu_1^{(3)}$ and $\mu_2^{(3)}$, as well as for the variances of the taintings, namely $\left( \eta_1^{(3)} \right)^2$ and $\left( \eta_2^{(3)} \right)^2$. If no information of that kind is available, take $\mu_1^{(3)} = \mu_2^{(3)} = 1/2$ and $\left( \eta_1^{(3)} \right)^2 = \left( \eta_1^{(3)} \right)^2 = 1/4$. Let $U_1, \ldots, U_k$ and $V_1, \ldots, V_l$ be the dollar-unit tainting samples taken from populations $B$ and $C$ respectively.

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Then the statistic

\[ A \cdot b^2(c_1U + c_2V) \]

is a \((1 - \alpha)\)-confidence upper bound for the total error \(E\).

**Proof of Corollary 3.** This follows directly from (1.1) and statement 3. □

As in the previous section, we can say that in general, bigger values of \(c = \max(c_1, c_2)\) will result in more conservative bounds for \(E\). Therefore, it is advised to choose \(k\) and \(l\) so that \(c\) is minimal.

### 4 Simulation results

In order to evaluate the performance of the new bounds presented in the sections 2 and 3 in auditing applications, computer simulations were used. The simulation design followed Grimlund and Felix (1987).

First, two test population \(B\) and \(C\) were generated. Since the proposed bounds only depend on the taintings, and not on the actual account sizes and error values, the simulated population consisted of the taintings corresponding to the individual dollars. Thus, instead of the accounts \(B_1, B_2, \ldots, B_k\) and the corresponding errors \(E_1, E_2, \ldots, E_k\), we consider the taintings \(T^{(i)} = \{t^{B_i}_1, t^{B_i}_2, \ldots, t^{B_i}_j\}\), where, assuming that the \(i\)-th dollar was taken from the \(j\)-th account,

\[ t^{B}_i = \frac{E^{B}_i}{B_j}. \]

It is easy to see that sampling with replacement from \(T^{(i)}\) results in the same distribution of samples as dollar-unit sampling from the population \(B\). The same is true for \(C\) and the combined population \(A\). The monetary values of both populations were taken to be equal to 10000 dollars, i.e. \(B = C = 10000\).

The distribution of taintings in each population was derived from the error model described in Grimlund and Felix (1987), which is commonly used in the simulations related to auditing problems. This model uses four parameters: \(r\) – the proportion of accounts that are in error relative to all accounts, \(p_1\) – proportion of non-100% overstatement errors among all erroneous items, \(p_2 = 1 - p_1\) – proportion of 100% overstatement errors and \(\nu_1\) – mean value of the chi-squared distribution used to generate non-100% overstatement errors. The actual values of the parameters used in our computations, as well as the mean value \(\mu\) and the standard deviation \(\sigma\) of the taintings in each population as well as the union \(B \cup C\) are presented in Table 1.
Table 1. Generating parameters and descriptive statistics of the two test populations.

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>C</th>
<th>B ∪ C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>0.05</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>$p_1$</td>
<td>0.95</td>
<td>0.8</td>
<td>–</td>
</tr>
<tr>
<td>$p_2$</td>
<td>0.05</td>
<td>0.2</td>
<td>–</td>
</tr>
<tr>
<td>$\nu_1$</td>
<td>0.05</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.00502</td>
<td>0.11680</td>
<td>0.06091</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.05337</td>
<td>0.27378</td>
<td>0.20501</td>
</tr>
</tbody>
</table>

Thus, each test population consisted of $(1 - r) \cdot 10000$ zero taintings, $r \cdot p_2 \cdot 10000$ taintings equal to 1 and $r \cdot p_1 \cdot 10000$ randomly generated taintings that followed chi-squared distribution with 1 d.f. scaled by $\nu_1$ and truncated at 1.

The proposed upper confidence bound $b^*_2$ has been compared with the bound $b_6$ from Bentkus and van Zuijlen (2003). Confidence level was taken to be 95% ($\alpha = 0.05$). It must be noted that a direct comparison with the well-known Stringer bound, as described in Bickel (1992), is not possible, since this bound does not allow an extension to the two-sample case.

The sample sizes $n = 30, 60, 120$ and 240 were chosen for the simulation, and each round was performed in the following way.

First, the desired number of samples was drawn randomly from the test populations. For the bound $b^*_2$, $n/2$ taintings were randomly drawn from each population (since the monetary values of the populations are the same, $\alpha_1 = \alpha_2 = 1/2$ and taking $k = l = n/2$ means sampling proportionally to the monetary value). For the bound $b_6$, $n$ taintings were drawn from the union $B \cup C$. The corresponding bounds were calculated and compared with the actual mean value of the items in the test population. Since the samples evaluated in each case were different and random, in order to obtain reliable results this procedure was repeated 10000 times for each sample size. Finally, average values, coverages and variabilities for the analyzed bounds were calculated. Here coverage is the percentage of rounds where the calculated bound was greater than or equal to the actual mean value, and the variability is the variance of the calculated bounds. In order to guarantee the absence of correlation in the data, a cryptographic pseudo-random number generator by Kelsey et al. (2000) was used to create the test populations and to draw the samples.

The following table presents the simulation results.

Table 2. Simulation results.

<table>
<thead>
<tr>
<th>Sample size</th>
<th>$\bar{b}^*_2$</th>
<th>$\bar{b}_6$</th>
<th>Cov$_{\bar{b}^*_2}$</th>
<th>Cov$_{\bar{b}_6}$</th>
<th>Var$_{\bar{b}^*_2}$</th>
<th>Var$_{\bar{b}_6}$</th>
<th>Var$_{\bar{b}^*<em>2}$/Var$</em>{\bar{b}_6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.21981</td>
<td>0.21915</td>
<td>100</td>
<td>100</td>
<td>0.003437</td>
<td>0.003710</td>
<td>0.926</td>
</tr>
<tr>
<td>60</td>
<td>0.16374</td>
<td>0.163287</td>
<td>99.97</td>
<td>99.86</td>
<td>0.001440</td>
<td>0.001542</td>
<td>0.934</td>
</tr>
<tr>
<td>120</td>
<td>0.12881</td>
<td>0.12874</td>
<td>99.90</td>
<td>99.80</td>
<td>0.000600</td>
<td>0.000665</td>
<td>0.901</td>
</tr>
<tr>
<td>240</td>
<td>0.10537</td>
<td>0.10541</td>
<td>99.76</td>
<td>99.81</td>
<td>0.000268</td>
<td>0.000290</td>
<td>0.922</td>
</tr>
</tbody>
</table>
Here \( \overline{b}_2 \) and \( \overline{b}_6 \) are the mean values; \( \text{Cov}_1 \) and \( \text{Cov}_2 \) are the coverage statistics; \( \text{Var}_2 \) and \( \text{Var}_6 \) are the variabilities for the bounds \( b_2 \) and \( b_6 \) respectively. In order to measure the relative advantage of sampling proportionally and using the bound \( b_2 \) compared to random sampling with \( b_6 \), the ratio \( \text{Var}_2 / \text{Var}_6 \) was calculated.

Simulation results can be summarized as follows.

- The proposed bounds with proportional subsample sizes offer lower variability compared to the case of random sampling from the combined population \( \mathbf{B} \cup \mathbf{C} \).
- The coverage is approximately the same in both cases.
- The tightness of both bounds used in the simulations is also approximately the same.

Therefore, proportional sampling and the bound \( b_2 \) are more effective than random sampling with the bound \( b_6 \).

It must be emphasized that the relation between confidence bounds for a parameter and bounds for tail probabilities (which is established by Statement 4 in the appendix) implies that, although very conservative, the presented bounds are in a certain sense the best possible, since they originate in the most accurate provable bounds for tail probabilities in a nonparametric setting. It is natural to expect that significant improvements in the tightness of these bounds can only be obtained by certain restrictions on the class of the possible tainting distributions.

5 Appendix A: Proof of Lemma 2

Lemma 2 follows directly from a more general statement that uses positive real numbers \( \alpha \) and \( \beta \), \( \alpha + \beta = 1 \), in place of \( k/n \) and \( k/n \).

We are going to use the following notation. Let \( \varepsilon \) be a Bernoulli random variable (that is, a random variable which assumes at most two different values) such that

\[
P\{\varepsilon = a\} = p, \quad P\{\varepsilon = b\} = q, \quad E\varepsilon = 0, \quad \varepsilon^2 = \sigma^2,
\]

for some \( b > 0 \), \( a < 0 \), \( \sigma^2 > 0 \) and \( 0 \leq p, q \leq 1 \). Using the conditions

\[
p + q = 1, \quad E\varepsilon = ap + bq = 0, \quad E\varepsilon^2 = a^2 p + b^2 q = \sigma^2
\]

we can write

\[
p = \frac{b^2}{b^2 + \sigma^2}, \quad q = 1 - p = \frac{\sigma^2}{b^2 + \sigma^2}, \quad a = -\frac{\sigma^2}{b}.
\]

For \( \varepsilon \geq 0 \), introduce the generating function

\[A = A(x) = \mathbb{E} e^{x \varepsilon} = p e^{ha} + q e^{hb},\]

where for brevity we write \( x = (b, \sigma^2) \). Write

\[f(x) = \ln A(x)\]
We shall prove that, for any \( h \geq 0 \), the function \( f \) satisfies the following convexity type inequality.

**Lemma 4.** Let \( 0 \leq \alpha \leq 1 \) and \( \beta = 1 - \alpha \). Write

\[
x = (b, \sigma) \quad \text{with} \quad b = \beta b_0 + \alpha b_1 \quad \text{and} \quad \sigma^2 = \beta \sigma_0^2 + \alpha \sigma_1^2 + \frac{(s + 1)}{2} \alpha \beta (b_0 - b_1)^2,
\]

and

\[
x_0 = x \bigg|_{\alpha = 0} = (b_0, \sigma_0^2), \quad x_1 = x \bigg|_{\alpha = 1} = (b_1, \sigma_1^2), \quad (5.1)
\]

with some

\[
b_0, b_1, \sigma_0^2, \sigma_1^2, h \geq 0.
\]

Then the smallest constant \( s \) such that the inequality

\[
\beta f(x_0) + \alpha f(x_1) \leq f(x)
\]

holds for all \( x_0, x_1 \) and \( 0 \leq \alpha \leq 1 \), is equal to 0. Moreover, (5.1) holds for all \( s \geq 0 \).

Inequality (5.1) extends Hoeffding’s (1963) Lemma 3 which is a particular case of (5.1) with \( b_0 = b_1 \).

**Proof of Lemma 4.** We start by showing that it suffices to prove (or disprove) (5.1) for \( h = 1 \). Indeed, if \( h = 0 \) then (5.1) becomes the equality \( \theta = 0 \). If \( h > 0 \), we can replace

\[
h b_0, h b_1, h \sigma_0, h \sigma_1
\]

by new variables

\[
b_0, b_1, \sigma_0, \sigma_1.
\]

Therefore we assume henceforth that \( h = 1 \).

Consider the function

\[
g(\alpha) = \ln A(x) - \beta \ln A(x_0) - \alpha \ln A(x_1), \quad 0 \leq \alpha \leq 1.
\]

(5.2)

This function satisfies

\[
g(0) = g(1) = 0.
\]

Therefore, in order to prove (5.1) it suffices to show that \( g \) is a concave function of \( \alpha \), that is, that

\[
g''(\alpha) \leq 0.
\]

(5.3)

In order to show that (5.1) does not hold for \( s < 0 \), it suffices for such \( s \) to find \( b_0, b_1, \sigma_0^2, \sigma_1^2 \geq 0 \) such that \( g \) is a strictly convex function of \( \alpha \), that is, that

\[
g''(\alpha) > 0, \quad \text{for all} \quad 0 \leq \alpha \leq 1.
\]

(5.4)

To simplify formulas, we introduce additional notation. Write

\[
B = p e^{-\vartheta} + q, \quad \vartheta = b - a, \quad g_0(\alpha) = \ln B.
\]
Then $A = e^b B$ and

$$g(\alpha) = C + g_0(\alpha), \quad C = b - \beta \ln A(x_0) - \alpha \ln A(x_1).$$

Since $C$ is a linear function of $\alpha$, we have $C'' = 0$. Therefore $g''$ and $g_0''$ have the same sign. Furthermore, $B^2 g_0'' = B'' B - B'^2$. Hence, instead of (5.3) (respectively (5.4)) it suffices to check that

$$B'^2 - B'' B \geq 0,$$  \hspace{1cm} (5.5)

and respectively

$$B'^2 - B'' B < 0.$$  \hspace{1cm} (5.6)

We have

$$B' = (p' - p''') e^{-\vartheta} + q'$$

and

$$B'' = (p'' - 2p' \vartheta' + p'\vartheta'') e^{-\vartheta} + q''.$$

Furthermore

$$B'^2 = (p'^2 - 2pp' \vartheta' + p^2 \vartheta'') e^{-2\vartheta} + (2p'q' - 2pq' \vartheta') e^{-\vartheta} + q'^2,$$

$$B'' B = (pp'' - 2pp' \vartheta' - p^2 \vartheta'' + p^2 \vartheta'^2) e^{-2\vartheta} + (p''q - 2p'q' \vartheta' - pqq' \vartheta'' + pqq'' + p'q') e^{-\vartheta} + qq''.$$

Hence

$$B'^2 - B'' B = m_1 e^{-2\vartheta} + m_2 e^{-\vartheta} + m_3$$

with

$$m_1 = p'^2 - pp'' + p^2 \vartheta'',$$
$$m_2 = 2p'q' - pq'' - 2pq' \vartheta' + 2p'q\vartheta' + pqq'' - pq\vartheta'^2,$$
$$m_3 = q''.$$

We have $q' = -p'$ and $q'' = -p''$, since $p + q = 1$. Replacing $q'$ and $q''$ by $-p'$ and $-p''$ respectively, we obtain

$$m_1 = p'^2 - pp'' + p^2 \vartheta'',$$
$$m_2 = -2p'^2 + pp'' - qp'' + 2p' \vartheta' + pq\vartheta' - pq\vartheta'^2,$$
$$m_3 = p''.$$

Introducing

$$u(\vartheta) = m_1 + m_2 e^{\vartheta} + m_3 e^{2\vartheta},$$

inequality (5.5) (respectively (5.6)) is equivalent to

$$u(\vartheta) \geq 0$$  \hspace{1cm} (5.8)
and respectively
\[ u(\vartheta) < 0. \] (5.9)

To simplify forthcoming calculations, we introduce a new parametrization. Write
\[ t = \frac{\sigma^2}{b^2}. \]

Then
\[ p = \frac{1}{1+t}; \quad q = \frac{t}{1+t}; \quad p' = -p^2t', \quad p'' = 2p^3t^3 - p^2t''. \] (5.10)

We introduce a new variable
\[ \delta = b_1 - b_0 > 0. \]

The assumption that \( \delta > 0 \) does not restrict generality. Indeed, if \( \delta = 0 \) then the inequality to prove reduces to the Hoeffding’s (1963) Lemma 3. Or one can derive the result by continuity arguments using the inequality for \( \delta \neq 0 \). If \( \delta < 0 \), then we can exchange roles of \( b_0 \) and \( b_1 \). Introduce new variables
\[ \sigma_0, \sigma_1, b_0 \]
by
\[ \sigma_0 = \delta \sigma, \quad \sigma_1 = \delta \sigma, \quad b_0 = \delta b_0. \]

Note that the variable
\[ t = \frac{\sigma_0^2 + \alpha \varphi + (s + 1)\alpha \beta \delta^2 / 2}{(b_0 + \alpha \delta)^2} = \frac{\sigma_0^2 + \alpha \varphi + (s + 1)\alpha \beta \delta^2 / 2}{(b_0 + \alpha)^2} \]
with \( \varphi = \sigma_1^2 - \sigma_0^2 \) and \( \varphi = \sigma_1^2 - \sigma_0^2 \) is independent of \( \delta \). Writing
\[ c = b_0 + \alpha, \quad \gamma = \frac{c}{p}, \]
we have
\[ t = \frac{\sigma_0^2 + \alpha \varphi + (s + 1)\alpha \beta \delta^2 / 2}{c^2}, \quad \delta = \delta \gamma \]
since \( \varphi = \frac{b + \sigma^2 / b = b/p = \delta}{c}\). Furthermore, we have
\[ \varphi' = \frac{\varphi' \gamma}{\gamma}, \quad \varphi'' = \frac{\varphi'' \gamma}{\gamma}. \]

Using the notation, we can rewrite (5.7) as
\[ m_1 = p^2 - pp'' + \frac{2p' \gamma''}{\gamma} \varphi, \]
\[ m_2 = -2p^2 + pp'' - eq'' + \frac{2p' \gamma''}{\gamma} \varphi + \frac{pq \gamma''}{\gamma} \varphi - pq \gamma^2 \varphi^2 + \varphi^2, \]
\[ m_3 = p^2 + pp''. \]

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Hence
\[ \gamma^2 m_1 = c_0 + c_1 \theta, \]
\[ \gamma^2 m_2 = d_0 + d_1 \theta + d_2 \theta^2, \]
\[ \gamma^2 m_3 = e_0. \] (5.11)

with some \(c_0, c_1, d_0, d_1, d_2, e_0\) independent of \(\theta\) such that
\[ c_0 = \gamma^2 (p''^2 - pp'''), \]
\[ c_1 = \gamma p' p''', \]
\[ d_0 = \gamma^2 (-2p''^2 + pp''' - qp'''), \]
\[ d_1 = 2p' \gamma p''' + pq\gamma'''', \]
\[ d_2 = -pq\gamma^2, \]
\[ e_0 = \gamma^2 (p''^2 + qp'''). \] (5.12)

We introduce the notation
\[ y = \gamma'. \]

Let us show that
\[ p' t' = p y - 1, \] (5.13)
\[ p' t'' = 2 - 4py + (1 - s)p, \] (5.14)
\[ p' = \frac{\gamma}{\gamma}, \] (5.15)
\[ p'' = \frac{2py^2 - 1 + s}{\gamma^2}, \] (5.16)
\[ \gamma''' = \frac{1 - s - 2y}{p\gamma}. \] (5.17)

Let us prove (5.13). Since \(\gamma = c/p\) and \(c' = 1\), we have
\[ y = \gamma' = \frac{1}{p} - \frac{cp'}{p^2}. \]

Using \(p' = -p''t'\) (cf. (5.10)), we derive (5.13).

Let us prove (5.14). We have
\[ t = \frac{u}{c^2}, \quad u = \tilde{\sigma}_0 + \alpha \tilde{q} + (s + 1) \alpha \beta / 2. \]

Hence
\[ t' = \frac{u'}{c^2} - \frac{2u}{c^3}, \quad ct' = \frac{u'}{c} - 2t \]
and, using \(u'' = -s - 1\),
\[ t'' = \frac{u''}{c^2} - \frac{2u'}{c^3} + \frac{6u}{c^4} = \frac{s + 1}{c^2} - \frac{4u'}{c^3} + \frac{6t}{c^2}. \]
Inserting \( \frac{ct'}{c} = ct' + 2t \) and using \( pctl' = py - 1 \) (cf. (5.13)), we have
\[
c^2t''' = -s - 1 - \frac{4u'}{c} + 6t = -s - 1 - 4ct' - 2t = 1 - s - 2(1 + t) - 4y + 4/p.
\]

Multiplying by \( p = 1/(1 + t) \), we derive (5.14).

Let us prove (5.15). We have \( p' = -p^2t' \) (cf. (5.10)), and an application of (5.13) together with \( \gamma = c/p \) yields (5.15).

Let us prove (5.16). By (5.10) we have \( p'' = 2p^2t' - p^2t'' \). Now an application of (5.13), (5.14) and \( \gamma = c/p \) yields (5.16).

To prove (5.17) we note that \( py' = c \). Differentiating twice, using \( c'' = 0 \), \( y' = y \) and (5.15), (5.16), we easily derive (5.17).

Inserting in (5.12) \( \gamma' = y \) and the values (5.13)–(5.17), we obtain
\[
\begin{align*}
c_0 & = 1 - 2py - p^2y^2 + p - ps, \\
c_1 & = -2py + p - ps, \\
d_0 & = 4py - 2qpy^2 - 2 + q - p + ps - qs, \\
d_1 & = 2py - 2qpy^2 + q - qs, \\
d_2 & = -qpy^2, \\
e_0 & = (1 - py)^2 + 2qpy^2 - q + qs.
\end{align*}
\]

Now we can start the proof of the positive part of the statement of the lemma or, equivalently, of (5.8). Since \( p\gamma^2 = c^2/p > 0 \), inequality (5.8) is equivalent to (cf. (5.11))
\[
w(\vartheta) \geq 0, \quad \text{for } \vartheta \geq 0,
\]
with
\[
w(\vartheta) = n_1 + n_2 e^\vartheta + n_3 e^{2\vartheta},
\]
where
\[
\begin{align*}
n_1 & = c_0 + c_1\vartheta, \\
n_2 & = d_0 + d_1\vartheta + d_2\vartheta^2, \\
n_3 & = e_0.
\end{align*}
\]

It suffices to prove (5.8) for \( s = 0 \). It is clear (cf. (5.18) and (5.20)) that the function \( s \mapsto w(s) \) is a linear increasing function of \( s \), that is, \( \partial_s w \geq 0 \) (here \( \partial_s \) stands for the partial derivative with respect to \( s \)). Indeed, using (5.18) and (5.20), we have
\[
\partial_s w = -p - p\vartheta + (p - q - q\vartheta) e^\vartheta + q e^{2\vartheta}.
\]

Using \( e^{2\vartheta} \geq e^\vartheta(1 + \vartheta) \) and \( e^\vartheta \geq 1 + \vartheta \) we get
\[
\partial_s w \geq -p - p\vartheta + p e^\vartheta \geq 0.
\]
Letting \( s = 0 \) in (5.18) yields
\[
\begin{align*}
   c_0 &= 1 - 2py - p^2y^2 + p, \\
   c_1 &= -2py + p, \\
   d_0 &= 4py - 2qpy^2 - 2 + q - p, \\
   d_1 &= 2py - 2py^2 + q, \\
   d_2 &= -qpy^2, \\
   e_0 &= (1 - py)^2 + 2qpy^2 - q.
\end{align*}
\] (5.21)

Let us show that the function \( p \mapsto w \) is a concave function of \( 0 \leq p \leq 1 \), that is, \( \partial^2_p w \leq 0 \). We have
\[
h(\vartheta) = \partial^2_p w = -2y^2 + (4y^2 + 2y^2 \vartheta^2) e^\vartheta - 2y^2 e^{2\vartheta}
\]
and
\[
\partial_\vartheta h(\vartheta) = (4y^2 + 4y^2 \vartheta + 2y^2 \vartheta^2) e^\vartheta - 4y^2 e^{2\vartheta}.
\]
Using \( e^{2\vartheta} \geq e^{\vartheta(1+\vartheta^2/2)} \), we obtain \( \partial_\vartheta h(\vartheta) \leq 0 \). Therefore the function \( \vartheta \mapsto h(\vartheta) \) is decreasing and
\[
\partial^2_\vartheta h(\vartheta) = h(\vartheta) - h(0) \leq 0, \quad \text{for } \vartheta \geq 0.
\]
Since the function \( p \mapsto w \) is a concave function of \( 0 \leq p \leq 1 \), in order to prove \( w \geq 0 \) it suffices to check that
\[
w \bigg|_{p=0} \geq 0 \quad \text{and} \quad w \bigg|_{p=1} \geq 0.
\] (5.22)

Using (5.21) we can rewrite (5.22) as
\[
h_0(\vartheta) = 1 + (\vartheta - 1) e^\vartheta \geq 0
\] (5.23)
and
\[
h_1(\vartheta) = 2 - 2y - y^2 + (1 - 2y) \vartheta + (4y - 3 + (2y - 2y^2) \vartheta) e^\vartheta + (y - 1)^2 e^{2\vartheta} \geq 0.
\] (5.24)

To prove (5.23) it suffices to note that \( h_0(0) = 0 \) and \( \partial_\vartheta h_0(\vartheta) = \vartheta e^\vartheta \geq 0 \), for \( \vartheta \geq 0 \).

To conclude the proof of (5.8) we have to check (5.24). It suffices to show that
\[
h_1(0) = \partial_\vartheta h_1(0) = 0, \quad \partial^2_\vartheta h_1(\vartheta) \geq 0, \quad \text{for } \vartheta \geq 0.
\]

We have
\[
\partial_\vartheta h_1(\vartheta) = 1 - 2y + (6y - 2y^2 - 3 + (2y - 2y^2) \vartheta) e^\vartheta + 2(y - 1)^2 e^{2\vartheta}
\] (5.25)
and
\[
\partial^2_\vartheta h_1(\vartheta) = (8y - 4y^2 - 3 + (2y - 2y^2) \vartheta) e^\vartheta + 4(y - 1)^2 e^{2\vartheta}.
\] (5.26)
Now (5.25) and (5.26) clearly imply \( h_1(0) = h'(0) = 0 \). Hence it remains to show that \( \partial^2_0 h(\theta) \geq 0 \), which is equivalent to

\[
8y - 4y^2 - 3 + (2y - 2y^2)\theta + 4(y - 1)^2 e^\theta \geq 0.
\]

We apply \( e^\theta \geq 1 + \theta + \theta^2/2 \). Then (5.27) is implied by

\[
g(y, \theta) = 1 + 2(y - 1)(y - 2)\theta^2 + 2(y - 1)^2 \theta^2 \geq 0.
\]

If \((y - 1)(y - 2) \geq 0\) then (5.28) obviously holds. If \((y - 1)(y - 2) < 0\), that is, if \(1 < y < 2\), then a unique minimizer of the quadratic function \( \theta \mapsto g(y, \theta) \) in (5.28) is \( \theta_0 = (2 - y)/(2(y - 1)) \) and we get

\[
\inf_{1 < y < 2} g(y, \theta) \geq \inf_{1 < y < 2} g(y, \theta_0) = \inf_{1 < y < 2} \left(1 - \frac{(2 - y)^2}{2}\right) = \frac{1}{2} > 0,
\]

which concludes the proof of (5.28) and of (5.8).

Let us prove the negative part of the statement of the lemma, that is, inequality (5.9). We assume that \( s < 0 \). Below \( C_k, k = 0, 1, 2, \ldots \) stand for positive constants which can depend only on \( s \). We have to choose \( b_0, b_1, \sigma_0^2, \sigma_1^2 > 0 \) such that (5.9) holds.

Instead of these parameters we can choose \( \delta, \sigma_0^2, \sigma_1^2 > 0 \). Let \( n \) be a sufficiently large natural number. Choose

\[
b_0 = 1, \quad \sigma_0^2 = n, \quad \sigma_1^2 = 2n.
\]

Then, writing \( d = \frac{1 + \delta}{2} \), we have

\[
c = 1 + \alpha, \quad \sigma^2 = n + \alpha n + d, \quad t = \frac{n + \alpha n + d}{(1 + \alpha)^2}.
\]

It is clear that \( t \to \infty, p \to 0, q \to 1 \) as \( n \to \infty \). Using \( p' = -p^2 \) (cf. (5.10)) and \( 1/p = 1 + t \), for \( y = \gamma' = (c/p)' \) we have

\[
y = \frac{1}{p} - \frac{c p'}{p^2} = 1 + t + ct'.
\]

It is clear that \( ct' = -2t + (n + d')/c \) and \( t = (n + \alpha n + d)/c^2 \). Hence, using \( c = 1 + \alpha \), relation (5.29) yields

\[
y = 1 - t + (n + d')/c = 1 + (cd' - d)/c^2.
\]

Therefore \( |y| \leq C_0 \). It is clear that

\[
\frac{s + 1}{2} - \alpha \beta \geq -C_1.
\]

We have

\[
p \leq 1/t \leq 4/(n - C_1) \leq 8/n, \quad \text{for } n \geq 2C_1.
\]
Using $p \leq 1$ and $|y| \leq C_0$, for the coefficients given by (5.18) we have

$$|c_0| + |c_1| + |d_0| + |d_1| + |d_2| \leq C_2. \quad (5.30)$$

In the case of $e_0$ we obtain

$$e_0 = p(1 - y)^2 + pqy^2 + qs \leq pC_3 + s/2 \leq s/4 \quad (5.31)$$

provided that $n$ is so large that $pC_3 \leq s/4$ and $q \geq 1/2$ (recall that $p \to 0$, as $n \to \infty$). We have

$$\gamma^2 w(\theta) \leq e^\theta (|m_1| |m_2| + m_3 e^\theta).$$

Hence, it suffices to show that $|m_1| + |m_2| + m_3 e^\theta < 0$. Using (5.30), (5.31) and $m_3 = e_0$, we derive

$$|m_1| + |m_2| + m_3 e^\theta \leq C_3 (1 + \theta^2) + \frac{s}{4} e^\theta < 0 \quad (5.32)$$

provided that we choose a sufficiently large $\theta > C_5$ (or, equivalently, $\delta > C_6$). Of course, while proving (5.32) we used that $s < 0$.

□

6 Appendix B: The relationship between confidence bounds for a parameter and bounds for tail probabilities

In order to prove the validity of our confidence bounds we have used the relation between upper bounds for the tail probabilities and confidence upper bounds for a parameter as described in Bentkus et al (2001). Let us establish the inverse relation, that is, show how to translate confidence upper bounds for a certain parameter into bounds for tail probabilities.

Let $\Theta \subset \mathbb{R}$ be a parameter space, and consider $T = \bigcup_{\theta \in \Theta} T_\theta$, where $T_\theta$ is a family of random variables with a characteristic $\theta$, where $\theta = \theta(T)$ depends only on the distribution of $T$. Suppose that there exists a $(1 - \alpha)$-confidence upper bound for the parameter $\theta$, i.e. a function

$$b : \mathbb{R} \times (0, 1) \to \mathbb{R},$$

which is increasing in the first argument, decreasing in the second argument and

$$\inf_{T \in T_\theta} P(\theta < b(T, \alpha)) \geq 1 - \alpha, \quad \forall \alpha \in (0, 1), \quad \forall \theta \in \Theta. \quad (6.1)$$

Furthermore, we assume that this function is right-continuous with respect to $\alpha$.

**Statement 4.** Let $V : \mathbb{R} \times \Theta \to [0, 1]$ be defined as

$$V(x, \theta) = \inf \{\alpha \in (0, 1) \mid b(x, \alpha) < \theta\}, \quad (6.2)$$
where $x$ is real and $\theta \in \Theta$. Then $V(x, \theta)$ is increasing in $x$, decreasing in $\theta$ and

$$\sup_{T \in I_0} P(T \leq x) \leq V(x, \theta), \quad \forall x \in \mathbb{R}, \quad \forall \theta \in \Theta. \tag{6.3}$$

**Proof of Statement 4.** Monotonicity properties follow from the monotonicity of $b$ and the definition of $V(x, \theta)$. In order to prove (6.3) let us substitute $\alpha$ in (6.1) by $V(x, \theta)$. If it is necessary, substitute $b(x, 1)$ by $\inf\{\theta \in \Theta\}$ and $b(x, 0)$ by $\sup\{\theta \in \Theta\} + \delta$ with an arbitrarily small $\delta > 0$. We have

$$P(\theta < b(T, V(x, \theta))) \geq 1 - V(x, \theta),$$

or equivalently

$$P(\theta \geq b(T, V(x, \theta))) \leq V(x, \theta). \tag{6.4}$$

From (6.2) and the monotonicity of $b$ in the second argument it follows that for any $\varepsilon > 0$ we have $b(x, V(x, \theta) + \varepsilon) < \theta$. Since the function $b$ is also right-continuous, we can write that

$$b(x, V(x, \theta)) = \lim_{\varepsilon \to +0} b(x, V(x, \theta) + \varepsilon),$$

and therefore

$$b(x, V(x, \theta)) \leq \theta. \tag{6.5}$$

Looking at the left-hand side of (6.4), we can write

$$P(\theta \geq b(T, V(x, \theta))) = P(T \in \{t | b(t, V(x, \theta)) \leq \theta\}).$$

Since $b$ is increasing in its first argument, from (6.5) we can conclude that

$$\{t | t \leq x\} \subset \{t | b(t, V(x, \theta)) \leq \theta\},$$

and therefore

$$P(T \leq x) \leq P(\theta \geq b(T, V(x, \theta))) \leq V(x, \theta). \square$$
References


