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Kyoto University
A note on asymptotic higher-order properties of a two-stage estimation procedure

(二段階推定法の高次漸近特性に関する一考察)\(^1\)

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1. Introduction

Let \(X_1, X_2, \ldots\) be a sequence of independent and identically distributed (i.i.d.) random variables from a normal population \(N(\mu, \sigma^2)\) where the mean \(\mu \in (-\infty, \infty)\) and the variance \(\sigma^2 \in (0, \infty)\) are both unknown. Having recorded \(X_1, \ldots, X_n\), we define \(\overline{X}_n = n^{-1} \sum_{i=1}^{n} X_i\) and \(S_n^2 = (n-1)^{-1} \sum_{i=1}^{n} (X_i - \overline{X}_n)^2\) for \(n \geq 2\). Let \(d \in (0, \infty)\) and \(\alpha \in (0, 1)\) be any preassigned numbers. On the basis of the random sample of size \(n\), we consider a confidence interval \(I_n = [\overline{X}_n - d, \overline{X}_n + d]\) for \(\mu\) with confidence coefficient \(1 - \alpha\). If we take the sample of size \(n\) such that

\[ n \geq a^2 \sigma^2 / d^2 \equiv n_0, \]

where \(a\) is the upper \(100 \times \alpha/2\%\) point of the standard normal distribution, then it holds that \(P(\mu \in I_n) \geq 1 - \alpha\) for all fixed \(\mu, \sigma^2, \alpha\) and \(d\). Unfortunately, \(\sigma^2\) is unknown, so we cannot use the optimal fixed sample size \(n_0\).

Stein’s two-stage procedure does not have the asymptotic second-order efficiency. Mukhopadhyay and Duggan (1997) proposed the following two-stage procedure, provided that \(\sigma^2 > \sigma_L^2\) where \(\sigma_L^2\) is positive and known to the experimenter. Let

\[ m = m(d) = \max \{m_0, [a^2 \sigma_L^2 / d^2]^* + 1\}, \]

where \(m_0 (\geq 2)\) is a preassigned integer and \([x]^*\) denotes the largest integer less than \(x\). By using the pilot observations \(X_1, \ldots, X_m\), calculate \(S_m^2\) and define

\[ N = N(d) = \max \{m, [b_m^2 S_m^2 / d^2]^* + 1\}, \]

where \(b_m\) is the upper \(100 \times \alpha/2\%\) point of the Student’s \(t\) distribution with \(m - 1\)

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degrees of freedom. If $N > m$, then take the second sample $X_{m+1}, \ldots, X_{N}$. Based on the total observations $X_1, \ldots, X_N$, consider the fixed-width confidence interval $I_N = [\bar{X}_N - d, \bar{X}_N + d]$ for $\mu$, where $\bar{X}_N = (X_1 + \cdots + X_N)/N$. Then, it is possible to show the exact consistency, that is, $P(\mu \in I_N) \geq 1 - \alpha$ for all fixed $\mu$, $\sigma^2$, $d$ and $\alpha$. Mukhopadhyay and Duggan (1997) showed that as $d \to 0$

$$\eta + o(n_0^{-1/2}) \leq E(N - n_0) \leq \eta + 1 + o(n_0^{-1/2}),$$

where $\eta = (1/2)(a^2 + 1)\sigma^2\sigma_{L}^{-2}$, and so the above two-stage procedure has the asymptotic second-order efficiency. Aoshima and Takada (2000) gave a second-order approximation to the average sample number: $E(N - n_0) = \eta + (1/2) + O(n_0^{-1/2})$ as $d \to 0$, and further Isogai et al. (2012) showed that $E(N - n_0) = \eta + (1/2) + O(n_0^{-1})$ as $d \to 0$. As for the coverage probability, Mukhopadhyay and Duggan (1997) showed that as $d \to 0$

$$1 - \alpha + o(n_0^{-1}) \leq P(\mu \in I_N) \leq 1 - \alpha + 2A n_0^{-1} + o(n_0^{-1}),$$

where $A = (1/2)a\phi(a)$ and $\phi(x)$ is the probability density function (p.d.f.) of the standard normal distribution. Aoshima and Takada (2000) gave a second-order approximation to the coverage probability:

$$P(\mu \in I_N) = 1 - \alpha + A n_0^{-1} + o(n_0^{-1}) \quad \text{as } d \to 0.$$

Define $T_d = b_m^2 S_m^2/d^2$, $t_d^* = n_0^{-1/2}(T_d - n_0)$ and $U_d = [T_d]^* + 1 - T_d$. Isogai et al. (2012) showed that as $d \to 0$

$$P(\mu \in I_N) = 1 - \alpha + A n_0^{-1} + \varepsilon_d n_0^{-3/2} + o(n_0^{-3/2}),$$

where $\varepsilon_d = -A(a^2 + 1)E(t_d^* U_d)$ and $|\varepsilon_d| \leq A(a^2 + 1)\sqrt{\sigma^2/(6\sigma_{L}^2)} + O(n_0^{-1/2})$. Uno (2013) established the asymptotic independence of $t_d^*$ and $U_d$, and obtained that

$$P(\mu \in I_N) = 1 - \alpha + A n_0^{-1} + o(n_0^{-3/2}) \quad \text{as } d \to 0. \quad (1)$$

In this article, we shall apply the result of Uno (2013) to the slight general case of Mukhopadhyay and Duggan (1999) in Section 2 and give some examples in Section 3.

2. Asymptotic theory

We consider the case of Mukhopadhyay and Duggan (1999) with $\tau = 1$. Let $X_1, X_2, \ldots$ be a sequence of i.i.d. random variables from a population. Several
optimal fixed sample sizes which arise from problems in sequential point and interval estimation may be written in the form

$$n_0 = q\theta/h,$$

where $q$ and $h$ are known positive numbers, but $\theta$ is the unknown and positive nuisance parameter. We assume that

$$\theta > \theta_L,$$

where $\theta_L(> 0)$ is known to the experimenter. Mukhopadhyay and Duggan (1999) proposed the following two-stage procedure. The initial sample size is defined by

$$m \equiv m(h) = \max\{m_0, \lfloor q\theta_L/h \rfloor^* + 1\},$$

where $m_0(\geq 2)$ is a preassigned positive integer. By the pilot sample $X_1, \ldots, X_m$ of size $m$, we consider an unbiased estimator $V(m)$ of $\theta$ satisfying $P\{V(m) > 0\} = 1$. Further, suppose that

$$Y_m = p_m V(m)/\theta$$

is distributed as $\chi_{p_m}^2$ with $p_m = c_1m + c_2$, where $p_m$ is a positive integer with a positive integer $c_1$ and an integer $c_2$, and $\chi_{p_m}^2$ stands for a chi-square distribution with $p_m$ degrees of freedom. We consider asymptotic theory as $h \to 0$, namely, $n_0 \to \infty$. Then,

$$m \to \infty \quad \text{and} \quad V(m) \xrightarrow{P} \theta \quad \text{as} \quad h \to 0,$$

where "$\xrightarrow{P}$" stands for convergence in probability. Let $q_m^*$ be positive where

$$q_m^* = q + c_3m^{-1} + O(m^{-2}) \quad \text{as} \quad h \to 0$$

with some real number $c_3$. Define

$$N \equiv N(h) = \max\{m, \lfloor q_m^* V(m)/h \rfloor^* + 1\}.$$

If $N > m$, then one takes the second sample $X_{m+1}, \ldots, X_N$. The total observations are $X_1, \ldots, X_N$. Throughout the remainder of this article, let

$$T_h = q_m^* V(m)/h, \quad t_h^* = n_0^{-1/2}(T_h - n_0) \quad \text{and} \quad U_h = [T_h]^* + 1 - T_h.$$

Then we obtain the following theorem.

**Theorem 1.** $U_h$ and $t_h^*$ are asymptotically independent as $h \to 0$. The asymptotic distribution of $U_h$ is uniform on $(0, 1)$; and the asymptotic distribution of $t_h^*$ is normal with mean 0 and variance $2\theta/(c_1\theta_L)$.
The proof of Theorem 1 is similar to that of Theorem (i) of Uno (2013). So we omit the details.

Let $\mathbb{R}^+ = (0, \infty)$ and suppose that $g: \mathbb{R}^+ \rightarrow \mathbb{R}^+$ is a three-times differentiable function and the third derivative $g^{(3)}(x)$ is continuous at $x = 1$. By Taylor's theorem, we have

\[
g(N/n_0) = g(1) + g'(1)n_0^{-1}(N - n_0) + (1/2)g''(1)n_0^{-2}(N - n_0)^2
+ (1/6)g^{(3)}(W)n_0^{-3}(N - n_0)^3,
\]

where $W$ is a random variable such that $|W - 1| < |(N/n_0) - 1|$. Uno and Isogai (2012) showed that if \{\(g^{(3)}(W)n_0^{-3/2}(N - n_0)^3; 0 < h < h_0\)\} is uniformly integrable for some sufficiently small $h_0 > 0$, then as $h \to 0$

\[
E\{g(N/n_0)\} = g(1) + B_0n_0^{-1} + o(n_0^{-3/2}),
\]

where

\[
B_0 = (1/2)g'(1) + \Delta(\theta/\theta_L), \quad \Delta = c_3q^{-1}g'(1) + c_1^{-1}g''(1),
\]

\[
\epsilon_h = g''(1)E(t_h^*U_h) \quad \text{and} \quad |
\epsilon_h| \leq |g''(1)|\sqrt{\theta/(6c_1\theta_L)} + O(n_0^{-1/2}).
\]

We obtain the next theorem.

**Theorem 2.** If \{\(g^{(3)}(W)n_0^{-3/2}(N - n_0)^3; 0 < h < h_0\)\} is uniformly integrable for some sufficiently small $h_0 > 0$, then as $h \to 0$

\[
E\{g(N/n_0)\} = g(1) + B_0n_0^{-1} + o(n_0^{-3/2}).
\]

**Proof.** It is easily seen from Lemma 2.2 of Mukhopadhyay and Duggan (1999) that \{|t_h^*U_h|; 0 < h < h_0\} is uniformly integrable for some sufficiently small $h_0 > 0$. Therefore, we have from Theorem 1 that $E(t_h^*U_h) = o(1)$ as $h \to 0$, which yields $\epsilon_h = o(1)$ in (2). \qed

**Remark.** If $\Delta = 0$, then the approximation of Theorem 2 does not depend on $\theta_L$ up to the order term.

Recall the fixed-width interval estimation of $\mu$ of $N(\mu, \sigma^2)$ described in Section 1. We take $q = a^2$, $h = d^2$, $\theta = \sigma^2$, $\theta_L = \sigma^2_L$, $V(m) = S_m^2$ and $q_m^* = b_m^2$. Then we have $p_m = m - 1$ ($c_1 = 1$, $c_2 = -1$) and $q_m^* = b_m^2 = a^2 + c_3m^{-1} + O(m^{-2})$ with $c_3 = (1/2)a^2(a^2 + 1)$. Taking $g(x) = 2\Phi(a\sqrt{x}) - 1$, where $\Phi$ is the cumulative distribution function of $N(0, 1)$, we have $g(1) = 1 - \alpha$, $g'(1) = a\phi(a)$ and $g''(1) = -(1/2)a(a^2 + 1)\phi(a)$. Thus, from Lemma 4.1 of Isogai et al. (2012) and Theorem
we obtain \( P(\mu \in I_N) = E\{g(N/n_0)\} = 1 - \alpha + (1/2)a\phi(a)n_0^{-1} + o(n_0^{-3/2}) \), which becomes the approximation (1). Note that \( \Delta \equiv c_3g^{-1}g'(1) + c_1^{-1}g''(1) = 0 \), and so \( B_0 = (1/2)a\phi(a) \) does not depend on \( \sigma_L^2 \).

3. Examples

We shall apply our theorem to three problems.

3.1. Bounded risk estimation of the normal mean

We consider a sequence of i.i.d. random variables \( X_1, X_2, \ldots \) from a normal population \( N(\mu, \sigma^2) \) where \( \mu \in \mathbb{R} = (-\infty, \infty) \) and \( \sigma^2 \in \mathbb{R}^+ \) are both unknown. We assume that there exists a known and positive lower bound \( \sigma_L^2 \) for \( \sigma^2 \) such that \( \sigma^2 > \sigma_L^2 \). Having recorded \( X_1, \ldots, X_n \), we define \( \overline{X}_n = n^{-1}\sum_{i=1}^{n}X_i \) and \( V(n) = (n-1)^{-1}\sum_{i=1}^{n}(X_i - \overline{X}_n)^2 \) for \( n \geq 2 \). On the basis of the random sample \( X_1, \ldots, X_n \) of size \( n \), we want to estimate \( \mu \) by \( \overline{X}_n \) under the loss function

\[
L_n = (\overline{X}_n - \mu)^2.
\]

Then, the risk is given by \( R_n = E(L_n) = \sigma^2/n \). For any preassigned \( w > 0 \), we hope that \( R_n = \sigma^2/n \leq w \), which is equivalent to

\[
n \geq \sigma^2/w \equiv n_0.
\]

Unfortunately \( \sigma \) is unknown, so we can not use the optimal fixed sample size \( n_0 \). Thus we define a two-stage procedure. Let

\[
m = m(w) = \max \left\{ m_0, \left[ \sigma_L^2/w \right]^* + 1 \right\},
\]

where \( m_0 \geq 4 \). By using the pilot observations \( X_1, \ldots, X_m \), we calculate \( V(m) \) and

\[
N = N(w) = \max \left\{ m, \left[ b_mV(m)/w \right]^* + 1 \right\},
\]

where \( b_m = (m-1)/(m-3) \). The risk is given by \( R_N = E(\overline{X}_N - \mu)^2 \). It follows from (7c.6.2) and (7c.6.7) with \( c^2 = w \) and \( b^2 = b_m \) in section 7c.6 of Rao (1973) that \( R_N \leq w \) for all fixed \( \mu, \sigma \) and \( w \). Therefore our requirement is fulfilled. In the notations of Section 2, note that \( h = w, \theta = \sigma^2, \theta_L = \sigma_L^2, q = 1, p_m = m - 1 \) \( (c_1 = 1, c_2 = -1) \) and \( q^*_m = b_m = 1 + 2m^{-1} + O(m^{-2}) \) with \( c_3 = 2 \). Taking \( g(x) = x^{-1} \) for \( x > 0 \), we have \( R_N = E(\sigma^2/N) = wE\{g(N/n_0)\} \) and \( \Delta = 0 \). From Proposition 1 of Uno and Isogai (2012) and Theorem 2, we obtain

\[
R_N/w = 1 - (1/2)n_0^{-1} + o(n_0^{-3/2}) \quad \text{as} \quad w \to 0.
\]
3.2. Fixed-width interval estimation of the negative exponential location

Let $X_1, X_2, \ldots$ be a sequence of i.i.d. random variables from a population having the following p.d.f.:

$$f(x) = \sigma^{-1} \exp\left\{-\frac{(x - \mu)}{\sigma}\right\}, \quad x > \mu,$$

where $\mu \in \mathbb{R}$ and $\sigma \in \mathbb{R}^+$ are both unknown. We assume that there exists a known and positive lower bound $\sigma_L$ for $\sigma$ such that $\sigma > \sigma_L$. For any preassigned numbers $d > 0$ and $\alpha \in (0, 1)$, we want to construct a confidence interval $I_n$ for the location parameter $\mu$ based on the random sample $X_1, \ldots, X_n$ of size $n$ such that the length of $I_n$ is fixed at $d$ and $P\{\mu \in I_n\} \geq 1 - \alpha$ for all fixed $\mu$ and $\sigma$. Having recorded $X_1, \ldots, X_n$, we define $X_{n(1)} = \min\{X_1, \ldots, X_n\}$ and $V(n) = (n - 1)^{-1} \sum_{i=1}^{n} (X_i - X_{n(1)})$ for $n \geq 2$, and consider a confidence interval $I_n = [X_{n(1)} - d, X_{n(1)}]$ for the location $\mu$. Then $P\{\mu \in I_n\} \geq 1 - \alpha$ for all fixed $\mu, \sigma, \alpha$ and $d$, provided

$$n \geq a \sigma / d \equiv n_0 \quad \text{with} \quad a = \ln(1/\alpha) \ (> 0).$$

Mukhopadhyay and Duggan (1999) proposed the following two-stage procedure. Let

$$m = m(d) = \max \left\{ m_0, \left[ a \sigma_L / d \right]^* + 1 \right\},$$

where $m_0 \geq 2$. By using the pilot observations $X_1, \ldots, X_m$, we calculate $V(m)$ and

$$N = N(d) = \max \left\{ m, \left[ b_m V(m) / d \right]^* + 1 \right\},$$

where $b_m$ is the upper 100$\alpha\%$ point of the $F$-distribution with 2 and $2(m - 1)$ degrees of freedom. Then the interval $I_N = [X_{N(1)} - d, X_{N(1)}]$ is proposed for $\mu$. It follows from (3.3) of Mukhopadhyay and Duggan (1999) that $P\{\mu \in I_N\} \geq 1 - \alpha$ for all fixed $\mu, \sigma, d$ and $\alpha$. Then, let $h = d, \theta = \sigma$, $\theta_L = \sigma_L, q = a, p_m = 2m - 2$ ($c_1 = 2, c_2 = -2$) and $q_m^* = b_m = a + (1/2) a^2 m^{-1} + O(m^{-2})$ with $c_3 = (1/2) a^2$ in the notations of Section 2. Taking $g(x) = 1 - e^{-ax}$ for $x > 0$, we have $P\{\mu \in I_N\} = E\{1 - \exp(-Nd/\sigma)\} = E\{g(N/n_0)\}$ and $\Delta = 0$. From Proposition 2 of Uno and Isogai (2012) and Theorem 2, we obtain

$$P\{\mu \in I_N\} = 1 - \alpha + (1/2) a \alpha n_0^{-1} + o(n_0^{-3/2}) \quad \text{as} \quad d \to 0.$$

3.3. Selecting the best normal population

Suppose there exist $k \geq 2$ independent populations $\pi_i, i = 1, \ldots, k$ and each $\pi_i$ has a normal distribution $N(\mu_i, \sigma^2)$, where the mean $\mu_i$ and the common variance $\sigma^2$ are unknown. Let us denote $\mu = (\mu_1, \ldots, \mu_k)'$ and write $\mu_{[1]} \leq \cdots \leq \mu_{[k-1]} \leq \mu_{[k]}$ for
the ordered $\mu$ values. Along the line of Bechhofer (1954), we consider the problem of selecting the population associated with the largest $\mu_{[k]}$, referred to as the best population, while guaranteeing

$$P\{CS\} \geq P^* \quad \text{whenever} \quad \mu \in \Omega(\delta)$$

(3)

for given $\delta (>0)$ and $P^* \in (k^{-1}, 1)$, where $\Omega(\delta) = \{\mu : \mu_{[k]} - \mu_{[k-1]} \geq \delta\}$ and the complementary subspace $\Omega^c(\delta)$ is called the indifference zone. Here and elsewhere, “CS” stands for “Correct Selection”. Let $X_{i1}, X_{i2}, \ldots$ be i.i.d. random variables from $\pi_i$ for $i = 1, \ldots, k$. Having recorded $X_{i1}, \ldots, X_{im}$ with fixed $n (\geq 2)$ from each $\pi_i$, we compute $\overline{X}_{im} = n^{-1} \sum_{j=1}^{n} X_{ij}$ and $\overline{X}_{[kn]} = \max_{1 \leq i \leq k} \overline{X}_{in}$. If $\sigma^2$ were known, one implements the following selection rule $(SR)$ for fixed $n$:

$$SR_n : \text{Select the population which gives rise to the largest sample mean} \ \overline{X}_{[kn]} \ \text{as the best population.}$$

(4)

Then, it follows from the equation (2.2) of Aoshima and Aoki (2000) that

$$\inf_{\mu \in \Omega(\delta)} P\{CS_{(SR_n)}\} = \int_{-\infty}^{\infty} \Phi^{k-1}(y + \sqrt{n\delta^2/\sigma^2})\phi(y)dy,$$

where $CS_{(SR_n)}$ stands for “Correct Selection” under the selection rule $SR_n$. The infimum is attained when $\mu_{[1]} = \cdots = \mu_{[k-1]} = \mu_{[k]} - \delta$, which is known as the least favorable configuration. Let

$$H(x) = \int_{-\infty}^{\infty} \Phi^{k-1}(y + \sqrt{x})\phi(y)dy, \quad x > 0$$

and $z = z(k, P^*)$ is a positive constant which satisfies the integral equation $H(z^2) = P^*$. The requirement (3) is satisfied if

$$n \geq z^2\sigma^2/\delta^2 \equiv n_0.$$

Since $\sigma^2$ is unknown, we can not use the optimal fixed sample size $n_0$. The two-stage procedure proposed by Bechhofer et al. (1954) satisfies (3) and hence it has the exact consistency.

Let us assume that $\sigma^2 > \sigma_L^2$ where $\sigma_L^2(>0)$ is known, and define

$$m = m(\delta) = \max \{m_0, \left[z^2\sigma_L^2/\delta^2\right]^* + 1\},$$

(5)

where $m_0 \geq 2$. Take the initial sample $X_{i1}, \ldots, X_{im}$ from each $\pi_i$ and compute $\overline{X}_{im}$, $i = 1, \ldots, k$ and $V(m) = k^{-1} \sum_{i=1}^{k} V_{im}$ where $V_{im} = (m-1)^{-1} \sum_{j=1}^{m} (X_{ij} - \overline{X}_{im})^2$. Aoshima and Aoki (2000) proposed

$$N = N(\delta) = \max \{m, \left[z^2V(m)/\delta^2\right]^* + 1\},$$

(6)
where \( t = t(k, P^*) \) is a positive constant such that \( E\{H(t^2 Y_m / p_m)\} = P^* \). Here, \( Y_m = p_m V(m)/\sigma^2 \) has the distribution \( \chi_m^2 \) with \( p_m = k(m - 1) \). In the notations of Section 2, note that \( q = z^2, \theta = \sigma^2, \theta_L = \sigma_L^2, h = \delta^2, c_1 = k, c_2 = -k \) and \( q_m^* = t^2 \). Secondly, one takes the additional sample \( X_{i(m+1)}, \ldots, X_{iN} \) of size \( N - m \) from each \( \pi_i \) and computes \( \overline{X}_{iN} = \sum_{j=1}^{N} X_{ij}/N, i = 1, \ldots, k. \) Then, we implement the selection rule \( SR_N \) given by (4) associated with \( \overline{X}_{[kN]} = \max_{1 \leq i \leq k} \overline{X}_{iN}. \) For the two-stage procedure defined by (5) and (6), Aoshima and Aoki (2000) showed the exact consistency, namely, \( \inf_{\mu \in \Omega(\delta)} P\{CS_{(SR_N)}\} \geq P^* \) for each fixed \( \delta \). It follows from the equation (2.9) of Aoshima and Aoki (2000) that as \( \delta \to 0 \)

\[
t^2 = z^2 + c_3 m^{-1} + O(m^{-2}), \quad \text{where } c_3 = - \frac{z^4 H''(z^2)}{kH'(z^2)}. \]

Here, \( H' \) and \( H'' \) are the first and second derivatives of \( H \), respectively. Taking \( g(x) = H(z^2 x) \) for \( x > 0 \), we have \( \inf_{\mu \in \Omega(\delta)} P\{CS_{(SR_N)}\} = E\{g(N/n_0)\} \) and \( \Delta = 0. \) From Proposition 4 of Uno and Isogai (2012) and Theorem 2, we obtain

\[
\inf_{\mu \in \Omega(\delta)} P\{CS_{(SR_N)}\} = P^* + (1/2)z^2 H'(z^2) n_0^{-1} + o(n_0^{-3/2}).
\]

Mukhopadhyay and Duggan (1999) proposed

\[
N^\dagger = N^\dagger(\delta) = \max \left\{ m, \left[ z^2 V(m)/\delta^2 \right]^* + 1 \right\}.
\]

For the two-stage procedure defined by (5) and (7), the exact consistency does not hold and \( \Delta = k^{-1}z^4 H''(z^2) \). Hence, from Proposition 3 of Uno and Isogai (2012) and Theorem 2, we have

\[
\inf_{\mu \in \Omega(\delta)} P\{CS_{(SR^\dagger_N)}\} = P^* + B_0^\dagger n_0^{-1} + o(n_0^{-3/2}),
\]

where \( B_0^\dagger = (1/2)z^2 H'(z^2) + k^{-1}z^4 H''(z^2)\sigma^2\sigma_L^{-2}, \) which depends on \( \sigma_L^2 \).

References


