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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)\textsuperscript{1}

Chikara Uno

Department of Mathematics, Akita University, Akita, 010-8502, Japan

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

$$m = m(d) = \max \{m_0, \lceil a^2 \sigma_L^2 / d^2 \rceil + 1\},$$

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

$$N = N(d) = \max \{m, \lceil b_m^2 S_m^2 / d^2 \rceil + 1\},$$

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 $I_N = [\overline{X}_N - d, \overline{X}_N + d]$ for $\mu$, where $\overline{X}_N = (X_1 + \cdots + X_N)/N$. 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 \( \chi^2_{p_m} \) with \( p_m = c_1 m + c_2 \),

where \( p_m \) is a positive integer with a positive integer \( c_1 \) and an integer \( c_2 \), and \( \chi^2_{p_m} \) 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

\[ q_m^* = q + c_3 m^{-1} + O(m^{-2}) \quad \text{as} \quad h \to 0 \]

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 $g: \mathbb{R}^+ \to \mathbb{R}^+$ 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 $h \to 0$

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

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). \(\square\)

**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 $q = a^2$, $h = d^2$, $\theta = \sigma^2$, $\theta_L = \sigma_L^2$, $V(m) = S_m^2$, 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 $\Delta \equiv c_3q^{-1}g'(1) + c_1^{-1}g''(1) = 0$, 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

$$m = m(w) = \max \{m_0, \lceil \sigma_L^2/w \rceil + 1\},$$

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

$$N = N(w) = \max \{m, \lceil b_mV(m)/w \rceil + 1\},$$

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

$$R_N/w = 1 - (1/2)n_0^{-1} + o(n_0^{-3/2}) \quad \text{as } w \to 0.$$
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

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

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

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

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

\[ P\{\mu \in I_N\} = 1 - \alpha + (1/2) a \alpha n^{-1}_0 + o(n^{-3/2}_0) \quad \text{as} \quad d \to 0. \]

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

$$P\{CS\} \geq P^* \quad \text{whenever} \quad \mu \in \Omega(\delta) \quad (3)$$

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 $X_{i1}, \ldots, X_{in}$ with fixed $n(\geq 2)$ from each $\pi_i$, we compute $\overline{X}_{in} = n^{-1} \sum_{j=1}^{n} X_{ij}$ 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 $n$:

$SR_n: \text{Select the population which gives rise to the largest sample mean } \overline{X}_{[kn]} \text{ as the best population.} \quad (4)$

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

$$m = m(\delta) = \max \left\{m_0, \left[ z^2\sigma_L^2/\delta^2 \right]^* + 1 \right\}, \quad (5)$$

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

$$N = N(\delta) = \max \left\{m, \left[ z^2V(m)/\delta^2 \right]^* + 1 \right\}, \quad (6)$$

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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 \( \chi_{p_m}^2 \) 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 \( \delta \rightarrow 0 \)

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

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

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

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


