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An alternative expression for the constant $c_4[n]$ with desirable properties

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Abstract. The constant $c_4[n]$ is commonly used in the construction of control charts and the estimation of process capability indices, where n denotes the sample size. Assuming normal distribution, the unbiased estimator of the population standard deviation is obtained by dividing the sample standard deviation by the constant $c_4[n]$. An alternative expression for $c_4[n]$ is proposed and the mathematical induction technique is used to prove its validity in the present paper. Some desirable properties are described. First, the suggested expression provides the exact value of $c_4[n]$. Second, it is not a recursive formula in the sense it does not depend on the previous sample size. Finally, the value of $c_4[n]$ can be directly computed for large sample sizes. Such properties suggest that the proposed expression may be a convenient solution in computer programming and it has direct applications in statistical quality control.

1. Introduction

The population standard deviation (σ) of a given variable X is a popular statistic in many disciplines. For instance, the parameter σ has a special relevance in statistical quality control, since the variability of production processes is traditionally associated with the standard deviation of the quality characteristic (see [1,2]). Accordingly, σ is used in different statistical techniques such as control charts [3–7], process capability indexes [8–11], acceptance sampling [12,13], etc. The parameter σ is usually unknown in practice and an estimator with desirable properties is required in this situation (see [14–17]). Let $x_1, \dots, x_n$ denote the values of X for a random sample with size n. The usual estimator of σ is the sample standard deviation $\widehat{\sigma} = (\widehat{\sigma}^2)^{1/2}$, where:

$$\widehat{\sigma}^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2, \quad (1)$$

is the sample variance and

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

is the sample mean. The term $n-1$ in Eq. (1) is the Bessel's correction, which is used to achieve an unbiased estimator, i.e., $E[\widehat{\sigma}^2] = \sigma^2$. Although $\widehat{\sigma}^2$ is an unbiased estimator of σ^2, the Jensen's inequality [18] can be used to show that $\widehat{\sigma}$ is a biased estimator of σ. Assuming a normal distribution, the unbiased estimator of σ (see [19–21]) is given by:

$$\widehat{\sigma}_{c4} = \frac{\widehat{\sigma}}{c_4[n]},$$

where the constant $c_4[n]$ is defined as:

$$c_4[n] = \frac{2^{1/2}}{(n-1)^{1/2}}\frac{\Gamma[n/2]}{\Gamma[(n-1)/2]}, \quad (2)$$

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$$\Gamma[a] = \int_0^\infty x^{a-1} e^{-x} dx$$

is the Gamma function. An alternative expression for $c_4[n]$ that also provides its exact value is given by:

$$c_4[n] = \begin{cases} \dfrac{c_4[2]}{(n-1)^{1/2}} \dfrac{2^{n-2}(n/2-1)!^2}{(n-2)!} & \text{if } n \text{ is even} \\ \dfrac{1}{(n-1)^{1/2} c_4[2]} \dfrac{(n-2)!}{2^{n-3}((n-3)/2)!^2} & \text{if } n \text{ is odd} \end{cases} \quad (3)$$

where $c_4[2] = (2/\pi)^{1/2}$. Note that $c_4[n]$ is a known constant in social sciences, and it has an especial relevance in statistical quality control. Many references tabulate the value of $c_4[n]$ for different values of n (see [2]). Various statistical software can be used to compute $c_4[n]$, but its value may not be available in the case of large samples. This is due to the fact that Eq. (2) depends on the quotient of two Gamma functions, and $\Gamma[a]$ tends to infinite as a increases. Similarly, the value of Eq. (3) cannot be directly obtained for large sample sizes since the factorial function also tends to infinite as its argument increases. For instance, both Microsoft Excel and the statistical software R (R Core Team [22]) give a numerical solution of $\Gamma[a]$ up to the value $a = 171.6144$, which implies that $c_4[n]$ based upon Eq. (2) cannot be computed when $n > 343$. In the case of using (3), both Microsoft Excel and R give a numerical solution of $c_4[n]$ up to $n = 172$. A possible solution is to use a recursive expression, i.e. the value of $c_4[n]$ may depend on $c_4[n-1]$ or previous values of n. A recursive expression is given by

$$c_4[n] = \frac{(n-2)^{1/2}}{(n-1)^{1/2} \quad c_4[n-1]}. \quad (4)$$

However, recursive expressions are generally more time consuming in practice, for example, when programming, as can be seen in Section 3. Alternatively, approximations may be used in the case of large sample sizes. Some examples are [19–23]:

$$c_4[n] \cong 1 - \frac{1}{4n} - \frac{7}{32n^2} - \frac{19}{128n^3},$$

$$c_4[n] \cong \frac{4(n-1)}{4n-3}.$$

We present an analytical expression for $c_4[n]$ (see Eq. (7)) that provides its exact value and can be directly computed for large sample sizes, since it does not depend on Gamma or factorial functions. Microsoft Excel and/or R can be easily used to compute the suggested expression under large sample sizes. Such programming details are available from the authors. The suggested expression may be a convenient solution in computer programming, since it is calculable for large sample sizes and less time consuming than recursive expressions.

2. A new expression for the constant $c_4[n]$

First, alternative expressions for $c_4[n]$ based on both even and odd values of n are derived. Second, we suggest an expression for $c_4[n]$ that can be used for any value of n. Finally, the mathematical induction technique is used to show the validity of the suggested expression.

The suggested expression for $c_4[n]$ is obtained by evaluating Eq. (4) at the first values of n. For instance, if we evaluate Expression (4) up to $n = 8$ we obtain (see Appendix A for more details):

$$c_4[8] = \frac{c_4[2]}{(n-1)^{1/2}} \frac{(n-2)!!}{(n-3)!!},$$

where:

$$n!! = \prod_{i=0}^{\lceil n/2 \rceil - 1} (n - 2i)$$

is the double factorial of n and $\lceil \cdot \rceil$ is the ceiling function, i.e. $\lceil a \rceil$ gives as output the smallest integer greater than or equal to a. Thereby, a possible expression for $c_4[n]$, when n is even, is given by:

$$c_4[n] = \frac{c_4[2]}{(n-1)^{1/2}} \frac{\prod_{i=2}^{n-2} i^{I_i}}{\prod_{i=3}^{n-3} i^{I_i^c}} = \frac{c_4[2]}{(n-1)^{1/2}} \frac{\prod_{i=2}^{n-2} i^{I_i}}{\prod_{i=2}^{n-2} i^{I_i^c}}$$

$$= \frac{c_4[2]}{(n-1)^{1/2}} \prod_{i=2}^{n-2} i^{I_i^*}, \quad (5)$$

where:

$$I_i = \begin{cases} 1 & \text{if } i \text{ is even} \\ 0 & \text{if } i \text{ is odd} \end{cases}$$

The indicator variables I_i^c and I_i^* are defined as

$$I_i^c = 1 - I_i = \begin{cases} 0 & \text{if } i \text{ is even} \\ 1 & \text{if } i \text{ is odd} \end{cases}$$

and:

$$I_i^* = I_i - I_i^c = \begin{cases} 1 & \text{if } i \text{ is even} \\ -1 & \text{if } i \text{ is odd} \end{cases}$$

Similarly, if we evaluate Expression (4) up to $n = 9$, we obtain (see Appendix A for more details):

$$c_4[9] = \frac{c_4[2]^{-1}}{(n-1)^{1/2}} \frac{(n-2)!!}{(n-3)!!}.$$

Hence, the suggested expression, when n is odd, is given by:

$$c_4[n] = \frac{c_4[2]^{-1}}{(n-1)^{1/2}} \frac{\prod_{i=3}^{n-2} i^{I_i^c}}{\prod_{i=2}^{n-3} i^{I_i}} = \frac{c_4[2]^{-1}}{(n-1)^{1/2}} \frac{\prod_{i=2}^{n-2} i^{I_i^c}}{\prod_{i=2}^{n-2} i^{I_i}}$$

$$= \frac{c_4[2]^{-1}}{(n-1)^{1/2}} \prod_{i=2}^{n-2} i^{-I_i^*}. \quad (6)$$

In the following, Theorem 1 provides a new expression for the constant $c_4[n]$, which is justified by Eqs. (5) and (6).

Theorem 1. For a fixed value of n, with $n \geq 4$, the function $c_4[n]$ can be expressed as:

$$c_4[n] = \frac{c_4[2]^{I_n^*}}{(n-1)^{1/2}} \prod_{i=2}^{n-2} i^{I_i^* I_n^*}, \quad \text{for } n \geq 4, \quad (7)$$

where I_n^* is defined by I_i^* after substituting i by n.

The proof of Theorem 1 can be seen in Appendix B. Note that this proof uses the principle of mathematical induction to demonstrate the validity of Eq. (7). In addition, note that Eq. (7) is valid for $n \geq 4$ due to the limits of the product operator of this equation, i.e. $\prod_{i=2}^{n-2}$ can be used, if $n \geq 4$.

3. Description of properties and discussion

We now describe some desirable properties for the proposed expression (7). First, we emphasize that the suggested expression provides the exact value of $c_4[n]$, i.e. approximations are not considered. Second, the existing expressions for $c_4[n]$ cannot provide its exact value in the case of large sample sizes, since they depend on Gamma or factorial functions and such functions tend to infinite as their corresponding arguments increase. However, we can observe that the suggested expression (Eq. (7)) does not suffer from this problem and it is calculable for the case of large sample sizes. In addition, we observe that the suggested expression (7) is not a recursive formula, since it does not depend on the previous sample size. Accordingly, it is expected that the suggested expression will be less time consuming than recursive expressions. A Monte Carlo simulation study is now carried out to compare empirically the computing times of both suggested and recursive expressions (Eqs. (7) and (4), respectively). The simulation study is programmed with the statistical software R and the codes are available under request. This empirical study consists of calculating Eqs. (7) and (4) under different sample sizes. This process is repeated 10^6 times and the total required time (in seconds) is computed. Results derived from this empirical study can be seen in Figure 1. We observe that the proposed expression for $c_4[n]$ is less time consuming than the recursive expression and the time difference increases as the sample size increases. For both suggested and recursive expressions, we also calculate the linear regression models between the sample size (x) and the total computing time (y), i.e.:

$$y_i = \beta_0 + \beta_1 x_i + u_i,$$

where u_i represents independent and identically distributed random variables with zero mean. In Table 1, we can observe the estimation of the regression coefficient (β_1) for the proposed and recursive expressions of $c_4[n]$. For the proposed expression, the value of the regression coefficient is $\widehat{\beta}_1 = 0.0479$, which is clearly smaller than the value of $\widehat{\beta}_1$ for the recursive expression ($\widehat{\beta}_1 = 0.1627$). In addition, the 95 percent confidence intervals for β_1 are computed and they are denoted

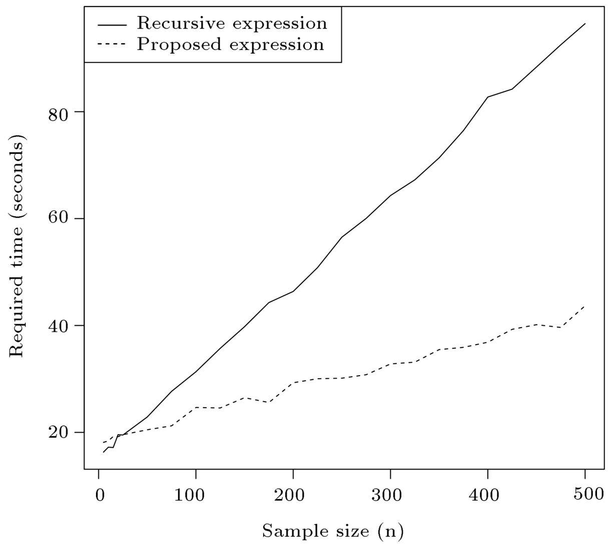

Figure 1. Total time required (in seconds) to calculate 10^6 times the constant c4 under Expressions (7) and (4) based on several sample sizes. The X axis shows the sample sizes (n).

Table 1. Regression coefficients ($\widehat{\beta}_1$), standard errors ($\widehat{SE}[\widehat{\beta}_1]$), 95 percent confidence intervals (L and U denote the lower and upper limits, respectively), and coefficients of determination (R^2) of the linear regression models for the sample size (n) and the total computing time of the simulation study.

Expression of $c_4[n]$	$\widehat{\beta}_1$	$\widehat{SE}[\widehat{\beta}_1]$	L	U	R^2 (%)
Proposed	0.0479	0.0010	0.0458	0.0501	99.0
Recursive	0.1627	0.0010	0.1606	0.1647	99.9

as $[L, U]$, where L and U are, respectively, the lower and upper confidence limits. Such confidence intervals indicate the existence of a significant difference between the slopes of both linear regression models. This implies that the difference between the computing time of the proposed and recursive expressions will be greater as the sample size increases.

The commented properties suggest that the proposed expression (Eq. (7)) may be a convenient solution in computer programming, since it is calculable for large sample sizes and less time consuming than recursive expressions.

4. Conclusion

The popular estimator of the population standard deviation is based on the constant $c_4[n]$ since it allows the estimator to be unbiased under normality. This estimator is often used in statistical quality control, as the standard deviation plays an important role in this context. For large sample sizes, the constant $c_4[n]$ cannot be computed when Eq. (3) is used because it depends on the factorial function. Similarly, various statistical software do not have the value of $c_4[n]$ when the sample size is large. The first solution is to use the recursive expression given by Eq. (4), but it is more time consuming when programming. The second solution consists on using existing approximations, but it is more interesting to use the real values. The main contribution of this paper is to provide a new analytical expression for $c_4[n]$ that solves this problem and avoids the mentioned disadvantages of existing solutions. These properties suggest that the proposed expression is an optimal solution in computer programming. A Monte Carlo simulation study compares the computing time of the suggested and recursive expressions. We observed a significant difference between the computing time of both expressions, and it increases as the sample size is larger.

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Appendix A

Expressions (5) and (6) are based on the evaluation of Eq. (4) up to $n = 9$. This appendix contains expressions of Eq. (4) when this equation is evaluated at $n = \{3, 4, \ldots, 9\}$:

$$c_4[3] = \frac{c_4[2]^{-1}}{2^{1/2}},$$

$$c_4[4] = \frac{2^{1/2}}{3^{1/2}c_4[3]} = \frac{2^{1/2}2^{1/2}c_4[2]}{3^{1/2}} = \frac{c_4[2]}{3^{1/2}}\frac{2}{1},$$

$$c_4[5] = \frac{3^{1/2}}{4^{1/2}c_4[4]} = \frac{3^{1/2}}{4^{1/2}}\frac{3^{1/2}}{c_4[2]}\frac{1}{2} = \frac{c_4[2]^{-1}}{4^{1/2}}\frac{3\times 1}{2},$$

$$c_4[6] = \frac{4^{1/2}}{5^{1/2}c_4[5]} = \frac{4^{1/2}}{5^{1/2}}\frac{4^{1/2}}{c_4[2]^{-1}}\frac{2}{3\times 1} = \frac{c_4[2]}{5^{1/2}}\frac{4\times 2}{3\times 1},$$

$$c_4[7] = \frac{5^{1/2}}{6^{1/2}c_4[6]} = \frac{5^{1/2}}{6^{1/2}}\frac{5^{1/2}}{c_4[2]}\frac{3\times 1}{4\times 2} = \frac{c_4[2]^{-1}}{6^{1/2}}\frac{5\times 3\times 1}{4\times 2},$$

$$c_4[8] = \frac{6^{1/2}}{7^{1/2}c_4[7]} = \frac{6^{1/2}}{7^{1/2}}\frac{6^{1/2}}{c_4[2]^{-1}}\frac{4\times 2}{5\times 3\times 1} = \frac{c_4[2]}{7^{1/2}}\frac{6\times 4\times 2}{5\times 3\times 1},$$

$$c_4[9] = \frac{7^{1/2}}{8^{1/2}c_4[8]} = \frac{7^{1/2}}{8^{1/2}}\frac{7^{1/2}}{c_4[2]}\frac{5\times 3\times 1}{6\times 4\times 2} = \frac{c_4[2]^{-1}}{8^{1/2}}\frac{7\times 5\times 3\times 1}{6\times 4\times 2}.$$

Appendix B

In this appendix we include the proof of Theorem 1. We use the principle of mathematical induction [24,25] to demonstrate the validity of the proposed expression (Eq. (7)). For the base case, we show that Theorem 1 holds for $n = 4$. By applying the recursive expression (Eq. (3)) at $n = 3$ and $n = 4$, we obtain:

$$c_4[4] = \frac{2^{1/2}}{3^{1/2}c_4[3]} = \frac{2^{1/2}2^{1/2}c_4[2]}{3^{1/2}} = \frac{c_4[2]\times 2}{3^{1/2}}. \quad \text{(B.1)}$$

From Eq. (7), we also obtain Eq. (B.1) and thus, Eq. (7) holds for $n = 4$. For the inductive step, we assume that Eq. (7) holds for some value $n \geq 4$ (induction hypothesis) and prove that $c_4[n+1]$ also holds. First, we assume that $n+1$ is even:

$$c_4[n+1] = \frac{c_4[2]^{I^*_{n+1}}}{n^{1/2}}\prod_{i=2}^{n-1} i^{I^*_i I^*_{n+1}} = \frac{c_4[2]}{n^{1/2}}\prod_{i=2}^{n-1} i^{I^*_i} = \frac{c_4[2]}{n^{1/2}}\frac{(n-1)!!}{(n-2)!!}.$$

Since $(n-1)! = (n-1)!!(n-2)!!$, we obtain:

$$c_4[n+1] = \frac{c_4[2]}{n^{1/2}}\frac{(n-1)!!^2}{(n-1)!}.$$

Since $n!! = 2^{n/2}(n/2)!$ (see [26]), we obtain:

$$c_4[n+1] = \frac{c_4[2]}{n^{1/2}}\frac{\left[2^{(n-1)/2}((n-1)/2)!\right]^2}{(n-1)!} = \frac{c_4[2]}{n^{1/2}}\frac{2^{n-1}((n-1)/2)!^2}{(n-1)!}.$$

From Eq. (3) we observe that:

$$c_4[n+1] = \frac{c_4[2]}{n^{1/2}} \frac{2^{n-1}((n-1)/2)!^2}{(n-1)!},$$

which proves that Eq. (7) holds when $n+1$ is even. Second, we assume that $n+1$ is odd:

$$c_4[n+1] = \frac{c_4[2]^{I^*_{n+1}}}{n^{1/2}} \prod_{i=2}^{n-1} i^{I^*_i I^*_{n+1}} = \frac{1}{n^{1/2} c_4[2]} \prod_{i=2}^{n-1} i^{-I^*_i}$$

$$= \frac{1}{n^{1/2} c_4[2]} \frac{(n-1)!!}{(n-2)!!}.$$

Since $(n-1)! = (n-1)!!(n-2)!!$, we obtain:

$$c_4[n+1] = \frac{1}{n^{1/2} c_4[2]} \frac{(n-1)!}{(n-2)!!^2}.$$

Since $n-2$ is even, using the previous property of the double factorial:

$$c_4[n+1] = \frac{1}{n^{1/2} c_4[2]} \frac{(n-1)!}{\left[2^{(n-2)/2}((n-2)/2)!\right]^2}$$

$$= \frac{1}{n^{1/2} c_4[2]} \frac{(n-1)!}{2^{(n-2)/2}((n-2)/2)!^2}.$$

From Eq. (3), we observe that:

$$c_4[n+1] = \frac{1}{n^{1/2} c_4[2]} \frac{(n-1)!}{2^{(n-2)/2}((n-2)/2)!^2},$$

which proves that Eq. (7) holds when $n+1$ is odd, and this completes the proof.

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