Accuracy estimate of technological processes as exemplified by construction works

A Kh Baiburin
Institute of Architecture and Constructions, South Ural State University, 76, Lenin ave., Chelyabinsk 454080, Russia
E-mail: baiburinak@susu.ru

Abstract. The article proposes a calculating method the accuracy of technological processes, taking into account the peculiar features of construction. It gives a graphical interpretation of process accuracy indicators for normal parameter distribution. It shows the differences in approaches to estimating accuracy. It provides actual data on the accuracy of installation works. The method of calculating the process accuracy takes into account the seriousness of defects and the criticality rating of buildings and structures. The article shows the relationship between the indicators of accuracy and defectiveness. The proposed calculation procedure ensures a more accurate estimate of the ratio of the tolerance to the parameter spread. The procedure allows us to estimate the accuracy of construction processes and, if necessary, to adjust the methods of work performance and quality control in order to achieve the specified accuracy.

1. Introduction
The accuracy of technological processes (TP) is defined as the proximity of the actual and nominal values of the TP parameters which ensure the quality of manufactured products. In construction and in other industries, analysis of TP accuracy involves the determination of certain indicators of TP accuracy and stability and the determination of its regularities over time [1-3]. Stability is a property of the TP characterized by the constancy of its parameters without outside interference.

As TP parameters are subject to technological variability and are of a random nature, statistical methods have been widely used in TP management [4-8]. Statistical methods of quality management include: statistical analysis of TP accuracy and stability; statistical control of TP; statistical acceptance control of the product quality; and the statistical quality assessment method [1,2,6,9-11].

The methods increase the efficiency of executive solutions based on the principles organizational and technological reliability of construction production [12] and scientifically valid choice of the options for operating activities realization in flow sheets, using innovational BIM technologies [13].

The construction industry has its own special characteristics which must be taken into account in statistical analysis and control of TP accuracy. These differences include: mass and production conditions; small volumes of batches and samples; the impossibility of culling; and the critical consequences of errors [3,14].

Technological process accuracy indicators are calculated based on the data of direct measurements, actual geodetic location sketches SP 126.13330.2012 "Geodetic works in building", laboratory control of materials [15-20]. The requirements of the standards "System of ensuring geometrical parameters
The purpose of the study is to refine calculation methods the technological process accuracy indicators for construction works.

2. Research methods
The defectiveness level for quantitative quality indicators is determined as the share of the distribution of the random variable of the parameter \( x \) outside the tolerance interval \([a, b]\):

\[
q = q_a + q_b;
\]

\[
q_a = 1 - \Phi \left( \frac{x - a}{S_x} \right);
\]

\[
q_b = 1 - \Phi \left( \frac{b - x}{S_x} \right),
\]

where \( \Phi \) represents the standard normal distribution function (the Laplace function) and \( S_x \) represents the sample standard deviation of parameter \( x \). If the boundaries \( a \) or \( b \) are not given, then \( q_a = 0 \) or \( q_b = 0 \), respectively.

The zero-defect level is:

\[
p = 1 - q.
\]

When justifying the calculation method and the estimated values of the construction process accuracy indicator, it is necessary to take into account that the conditions of construction operations are characterized by the significant influence of random factors on technological variability of parameters compared to other industries. The volumes of samples in construction are less; production is not mass, but piece. The set of deviations and defects in each capital construction item (even in standard ones) is unique.

In the conditions of construction operations, it is proposed to determine the technological process accuracy indicator when the parameter is limited from both sides \( a \leq x \leq b \) by the formula:

\[
K_f = \frac{\Delta x}{2t_{1-\alpha/2(v)}S_x} \leq \frac{\delta x}{t_{1-\alpha/2(v)}S_x},
\]

where \( \Delta x \) – standard tolerance (for a symmetric tolerance scope \( \Delta x = 2\delta x \)); \( \delta x \) – permissible deviation; \( t_{1-\alpha/2(v)} \) – quantile of \( t \)-distribution determined depending on the degree of freedom \( v=n-1 \) and the confidence level \( 1-\alpha/2 \); and \( S_x \) – standard deviation of the parameter.

When the parameter is limited from below \( a \leq x \) or from above \( x \leq b \), it is proposed to determine the accuracy indicator by the formulas, respectively:

\[
K_f = \frac{x - a}{t_{1-\alpha(v)}S_x}, \quad K_f = \frac{b - x}{t_{1-\alpha(v)}S_x}.
\]

The fractile \( t_{1-\alpha(v)} \) in formulas (3), (4) is determined depending on the confidence level \( 1-\alpha \) and the degrees of freedom \( v = n-1 \). For large (combined) samples at \( n > 120 \) it is proposed to take the quantiles \( t_{1-\alpha/2(v)} \) or \( t_{1-\alpha(v)} \) depending on the seriousness of defect or the criticality class of the structure according to Table 1.
Table 1. Values of the fractile of t-distribution.

| t-distribution fractile at $a \leq x \leq b$ | Seriousness of the defect | Criticality class | $\alpha$ |
|---------------------------------------------|---------------------------|-------------------|---------|
| $1.645$ | $1.282$ | Minor | Reduced, $\gamma \geq 0.8$ | $0.90$ |
| $1.960$ | $1.645$ | Serious | Normal, $\gamma \geq 1.0$ | $0.95$ |
| $2.576$ | $2.326$ | Critical | Increased, $\gamma \geq 1.1$ | $0.99$ |

Note: $\gamma$ represents the criticality-based safety factor utilized according to the requirements of the technical regulations on the safety of buildings and structures (the federal law 384-FZ, art.16).

Thus, as opposed to mass industrial production, where accuracy is usually determined with respect to three-sigma ($\pm 3\sigma$) probability intervals, intervals $(1.28–2.58) S_x$ are proposed to control the accuracy of construction processes, depending on the significance of deviations and the criticality level of the structure.

These proposals are consistent with the studies [3,15], in which the control boundaries for construction and geodetic works are recommended to be equal to $\pm (2–3)\sigma$. The studies [3,15-17] have shown that actual spreads can overlap the tolerances already at $\pm (1–2)\sigma$.

The coefficient of the technological process accuracy reserve is

$$K_S = 0,5 - K_{CM} - 0,5 / K_T,$$

where $K_{CM}$ represents the displacement coefficient calculated in the absolute value by the formula

$$K_{cm} = \left|\bar{x} - x_c\right| / \Delta x,$$

where $x_c$ represents the parameter value corresponding to the middle of the tolerance space. If the parameter is limited from below or from above, $K_{CM} = 0$.

The defectiveness (inconsistency) level can be calculated from the values of the accuracy indicator $K_T$ and the displacement coefficient $K_{CM}$ by the formulas:

- if the parameter is limited from both sides

$$q = 2 - \Phi\left\{2t_{1-\alpha/2}(v)K_T(0,5 + K_{CM})\right\} - \Phi\left\{2t_{1-\alpha/2}(v)K_T(0,5 - K_{CM})\right\};$$

- if the parameter is limited from one side:

$$q = 1 - \Phi(t_{1-\alpha/2}(v)K_T).$$

The control accuracy indicator was calculated by the formula:

$$K_{rc} = \delta_{x_{met}} / \Delta x,$$

where $\delta_{x_{met}}$ represents the limiting error of control measurements; $\Delta x$ represents the tolerance of the parameter $x$.

If the parameter is limited from below $a \leq x$ or from above $x \leq b$, the control accuracy indicator was determined by the formulas, respectively:

$$K_{rc} = \delta_{x_{met}} / (\bar{x} - a), \quad K_{rc} = \delta_{x_{met}} / (b - \bar{x}).$$

3. Results and discussion

Taking into account the increased technological variability, the random deviation $S_x$ is used instead of the general standard deviation $\sigma$, and the number of deviations providing a certain zero-defect level is assumed not to be equal to three, but rather depends on the sample size and the required probability (see Table 1). Let us compare the values of the accuracy indicator of some construction processes...
obtained from statistical data [15] of the position of the assembled structures of industrial buildings (Table 2).

| Controllable deviations                                      | n   | $S_x$, mm | $\Delta x$, mm | $\Delta x/6S_x$ | $\Delta x/4S_x$ | $\Delta x/2tS_x$ |
|--------------------------------------------------------------|-----|-----------|----------------|-----------------|-----------------|-----------------|
| **Installation of steel structures**                         |     |           |                |                 |                 |                 |
| Deviation of foundation marks                                | 151 | 7.71      | ±5             | 0.216           | 0.324           | 0.328           |
| Deviation of base plate marks                                | 147 | 2.24      | ±2             | 0.298           | 0.446           | 0.452           |
| Deviation from the column vertical                           | 278 | 15.10     | ±12            | 0.265           | 0.397           | 0.404           |
| Displacement of columns from axes                            | 163 | 5.40      | ±5             | 0.309           | 0.463           | 0.469           |
| Displacement of crane beams from axes                        | 293 | 6.60      | ±5             | 0.253           | 0.379           | 0.385           |
| **Installation of reinforced concrete structures**            |     |           |                |                 |                 |                 |
| Deviation of foundation marks                                | 112 | 28.6      | –20            | 0.233           | 0.350           | 0.422           |
| Displacement of column head marks                            | 214 | 7.24      | ±10            | 0.460           | 0.691           | 0.701           |
| Deviation from the column vertical $h=10$ m                   | 160 | 7.53      | ±20            | 0.885           | 1.328           | 1.345           |
| Deviation from the column vertical $h=15$ m                   | 540 | 9.65      | ±20            | 0.691           | 1.036           | 1.055           |
| Deviation from the column vertical $h=20$ m                   | 136 | 10.32     | ±25            | 0.807           | 1.211           | 1.225           |
| Deviation from the column vertical $h=25$ m                   | 230 | 12.53     | ±25            | 0.665           | 0.998           | 1.013           |
| Deviation from the column vertical $h=30$ m                   | 156 | 16.21     | ±30            | 0.617           | 0.925           | 0.937           |
| Displacement of columns from axes                            | 238 | 5.71      | ±8             | 0.467           | 0.701           | 0.711           |
| Displacement of beams from axes                              | 185 | 5.81      | ±8             | 0.459           | 0.688           | 0.698           |

Note: $n$ – sample volume; $\Delta x$ – systematic parameter deviation; $S_x$ – standard deviation; $\Delta x$ – standard tolerance; $t$ – fractile of $t$-distribution.

When comparing the calculation results, it is established that the difference between the values obtained according to the industry standards $6S_x$ and by formula (3) is about 34%. The difference between the indicators calculated at $4S_x$ and $2tS_x$ is about 2%. At the same time, taking into account the significance of deviations or building criticality level, this difference can already reach 30%. Thus, the proposed calculation procedure allows us to 2–34% more accurately estimate the ratio of the tolerance to the parameter spread. For samples $n = 30–120$, the $K_T$ estimate accuracy is increased by 9–17%, which is significant when adjusting the accuracy according to the structural safety condition [17].

As can be seen from the data in Table 2, the accuracy indicator of the processes of assembling building structures rarely exceeds one. This indicates the low accuracy and lack of control of most construction processes under the existing system of tolerances and the achieved technological level. Thus, the technological process accuracy standards adopted in mass production are not applicable in construction.

This conclusion is confirmed by the results of the authors' studies of work accuracy during the construction of civil buildings [16,17], in which the zero-defect level and process accuracy were estimated not only by geometric parameters, but also by the parameters of the material, bonds, and seams. In this case, the deviations were divided into critical, serious, and minor by their influence on the load-bearing capacity of structures.

As a result of industrial studies, it has been established that the process accuracy varies from 0.62 to 1.04 with a mean value of 0.75. The defectiveness level for critical defects is 0.01–0.02, excluding stonework emissions, in which gross mistakes were made in reinforcing bearing walls and pillars. The estimate of this indicator, justified in [16,17], is 0.015, which fully corresponds to the studied capabilities of construction processes. The defectiveness in serious and minor deviations equal to 0.35–0.36 cannot be considered satisfactory.
The mean values of the defectiveness and the accuracy of the studied processes are given in Table 3.

**Table 3. Estimate of the defectiveness and accuracy of construction processes.**

| Type of construction works          | Values of the defectiveness $q$ and accuracy $K_T$ indicators for the deviations |
|-------------------------------------|-----------------------------------------------|
|                                     | Critical | Serious | Minor |
| Foundation arrangement              | 0.02     | 1.25    | 0.22  |
| Installation                        | 0.02     | 0.80    | 0.41  |
| Stonework                           | 0.38$^a$ | 0.48$^a$| 0.39  |
| Reinforced concrete works           | 0.01     | 1.06    | 0.42  |
| Mean value                          | 0.02     | 1.04    | 0.36  |

$^a$ Excluded from the mean as emissions (gross errors in the form of the stonework reinforcement).

The justification of the estimated values of the accuracy indicator will be based on the preset defectiveness standards [15,16]. There is a functional relationship (7) between the defectiveness level and the process accuracy indicator, from which at $K_{сm} = 0$ we receive

$$q = 2 \cdot \left(1 - \Phi(t_{1-a}/2 K_T)\right).$$

Let us express the accuracy indicator

$$K_T = \frac{u_{1-q}/2}{t_{1-a}/2},$$

where $u_{1-q}/2$ – fractile of the function of the standard normal distribution law $\Phi(u)$ of level $1-\alpha/2$ and $t_{1-a}/2$ – fractile of $t$-distribution of level $1-\alpha/2$.

When the parameter is limited from one side, we will obtain from (8)

$$K_T = \frac{u_{1-q}}{t_{1-a}}.$$  

At the estimated values of the defectiveness $q$ justified in [16], using formulas (12) and (13), we will calculate the limit values of the accuracy indicator $K_T$ for various defects when the parameter is limited from both sides $a \leq x \leq b$ or from one side $a \leq x \leq b$. The fractile of the distribution $t_{1-a}$ will be taken from Table 1. The results of calculating the estimated values of the accuracy indicator $K_T$ are shown in table 4.

Based on the calculating results the indicator $K_T$, it is established that for the "unacceptable" category (with a defectiveness level of 0.10 and 0.04), the average values of the accuracy indicator are 0.732 and 0.998; for the "acceptable" quality category (with a defectiveness level of 0.015 and 0.0025) – 0.919 and 1.192, respectively.

Considering the studies results [2,4,9,11,14,17,18], we will take the following values as the lower estimated values of the accuracy indicator 0.67 and 1.00, and as upper values – 1.00 and 1.33 (Table 2). It follows from the results of the production studies that the proposed estimates of the accuracy indicator are assigned taking into account the real capabilities of technological processes and the base level of construction operations. With an increase in the technological level of works and the development of the construction industry base, these estimation criteria can be revised. Thus, based on the above justifications, and taking into account the results of analyzing domestic and foreign studies, we established the criteria for estimating technological process accuracy (Table 5).

The requirements of the standards "System for ensuring the accuracy of geometric parameters in construction", recommendations for accuracy calculation [19], as well as the results of the studies
[2,3,9,11,17] were taken into account for justifying the control accuracy indicator $K_{TK}$. Usually, when control accuracy is low or when the measurement error exceeds 10–20% of the tolerance value, the measurement results are considered to be incorrect, and either corresponding corrections or repeated measurements are required.

The estimation criteria specified in Table 4 can be used in relevant documents: standards of self-regulatory organizations, enterprise standards, quality control charts, procedures, instructions.

### Table 4. Results of calculating the process accuracy indicator.

| Seriousness of defect | Tolerance | $t_\alpha$ | $q$ | $1-q/2$ | $u_{1-q/2}$ | $K_T$ |
|----------------------|-----------|------------|-----|---------|------------|------|
| Critical             |           | 2.576      | 0.0025 | 0.9775  | 2.807      | 1.090 |
| $a \leq x \leq b$    |           | 2.576      | 0.015  | 0.9925  | 2.432      | 0.944 |
|                      |           | 2.576      | 0.04   | 0.980   | 2.054      | 0.797 |
|                      |           | 2.326      | 0.0025 | 0.9975  | 2.807      | 1.207 |
| $a \leq x (x \leq b)$|           | 2.326      | 0.015  | 0.985   | 2.170      | 0.933 |
|                      |           | 2.326      | 0.04   | 0.960   | 1.751      | 0.753 |
|                      |           | 1.960      | 0.015  | 0.985   | 2.170      | 1.107 |
| $a \leq x \leq b$    |           | 1.960      | 0.04   | 0.980   | 2.054      | 1.048 |
|                      |           | 1.960      | 0.10   | 0.950   | 1.645      | 0.839 |
| Serious              |           | 1.645      | 0.015  | 0.985   | 2.170      | 1.319 |
| $a \leq x (x \leq b)$|           | 1.645      | 0.04   | 0.960   | 1.751      | 1.064 |
|                      |           | 1.645      | 0.10   | 0.900   | 1.282      | 0.779 |
|                      |           | 1.645      | 0.04   | 0.960   | 1.751      | 1.064 |
|                      |           | 1.645      | 0.10   | 0.950   | 1.645      | 1.000 |
| Minor                |           | 1.645      | 0.25   | 0.875   | 1.150      | 0.699 |
| $a \leq x (x \leq b)$|           | 1.282      | 0.04   | 0.960   | 1.751      | 1.366 |
|                      |           | 1.282      | 0.10   | 0.900   | 1.282      | 1.000 |
|                      |           | 1.282      | 0.25   | 0.750   | 0.674      | 0.526 |

### Table 5. Estimates of statistical indicators.

| Name of indicator | unacceptabe stage 1 | unacceptable stage 2 | acceptable stage 1 | acceptable stage 2 |
|-------------------|----------------------|----------------------|--------------------|--------------------|
| Defectiveness level $q$ in case of defects: | | | | |
| critical          | 0.04                 | 0.015                | 0.015              | 0.0025             |
| serious           | 0.10                 | 0.04                 | 0.04               | 0.015              |
| minor             | 0.25                 | 0.10                 | 0.10               | 0.04               |
| weighted mean     | 0.08                 | 0.03                 | 0.03               | 0.01               |
| Process accuracy indicator $K_T$ | 0.67                 | 1.00                 | 1.00               | 1.33               |
| Control accuracy indicator $K_{TK}$ | 0.20                 | 0.15                 | 0.10               | 0.10               |

Note: 1st stage – before the introduction of statistical control; 2nd stage – after the introduction of statistical control of technological processes.

### 4. Conclusion

Considering the peculiar features of the construction industry, we specified a procedure for calculating the accuracy indicators of construction processes, taking into account the seriousness of defects, the distribution type of the quality parameter, and the criticality rating of the structure. The proposed procedure for calculating the process accuracy indicator allows us to 5-34% more accurately estimate the ratio of the tolerance to the parameter spread, which is important when adjusting the accuracy by the safety condition.
Based on the conducted research and analysis of the standards and the known works, we proposed the criteria for estimating the accuracy indicators. Based on the permissible defectiveness levels and the observed technological level, we justified the estimates of the accuracy indicators of technological processes.

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