http://doi.org/10.35784/iapgos.7398

received: 02.03.2025 | revised: 16.03.2025 | accepted: 19.03.2025 | available online: 31.03.2025

STATISTICAL RELIABILITY OF DECISIONS ON CONTROLLED PROCESS FAULTS

Yevhen Volodarskyi[1], Oleh Kozyr[1], Zygmunt L. Warsza[2]

[1]National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Department of Information and Measuring Technologies, Kyiv, Ukraine, [2]Polish Metrological Society, Warsaw, Poland

Abstract. *The article considers the issues of using control charts to detect the disruption of the technological process. The possible influence of measurement error on the correctness of decisions is considered. To ensure the statistical reliability of the decisions made, their plausibility, a priori probability is used. The effectiveness of assessing the compliance of the technological process with established standards is discussed, when the distributions of possible values of its parameters and errors of their measurements are uniform.*

Keywords: statistical reliability of decisions, erroneous decisions, quality control, conformity assessment, measurement errors, a-posteriori probability

STATYSTYCZNA WIARYGODNOŚĆ DECYZJI O WADLIWOŚCI KONTROLOWANEGO PROCESU

Streszczenie. *W artykule rozważono kwestie wykorzystania kart kontrolnych do wykrywania zakłóceń procesu technologicznego. Uwzględniono możliwy wpływ błędu pomiarowego na poprawność podejmowanych decyzji. Dla zapewnienia statystycznej wiarygodności podejmowanych decyzji wykorzystuje się ich prawdopodobieństwo a priori. Omówiono skuteczność oceny zgodności procesu technologicznego z ustalonymi standardami, gdy rozkłady możliwych wartości jego parametrów i błędów ich pomiarów są jednorodne.*

Słowa kluczowe: statystyczna wiarygodność decyzji, błędne decyzje, kontrola jakości, ocena zgodności, błędy pomiarowe, prawdopodobieństwo a-posteriori

Introduction

In production, the random nature of destabilizing factors leads to the dispersion of values of characteristic parameters of products. The deviation of a parameter from its nominal value is determined by random errors in production, which, under a certain scheme of the technological process, are characterized by a specific theoretical law of distribution of possible values.

For many years, there was only one, albeit very expensive, way to ensure product quality, which was based on checking the inspection of finished products for compliance with specified/established standards. The objectives of this approach are to divide products into those suitable for performing the proper functions or unsuitable, that is, to reduce the risk of further use of non-conforming products.

By comparing the characteristics or indicators of its properties with pre-established requirements in the form of standards, the essence of conformity assessment is to obtain initial information about the actual state of a given object [1].

Walter Shewhart, later a well-known consultant and specialist in the field of quality management, proposed the idea of managing technological processes to prevent the occurrence of product non-conformities with standards. For this purpose, he developed a simple tool based on the methods of probability theory and mathematical statistics. It made it possible to maintain the technological process in a statistically stable state and thereby prevent the occurrence of product non-conformities with standards. This tool, called Shewhart control charts [3], gave rise to a new concept of quality assurance. This concept is based on that quality should be created by the production process, and not by checking its results. In this sense, it is always too late to control, because the identified non-conformity is already an event that has occurred and cannot be prevented. But it is possible to prevent the occurrence of non-conformity if proactive management of process characteristics is carried out, i.e., controlled.

Standards are set or selected (calculated) based on the functional purpose of the object. Conformity assessments are carried out to establish the actual state of the object, i.e. its compliance with the standards [8].

The initial information used to assess compliance is a priori probabilities based on facts that have been confirmed over time. The facts can be evaluated based on established knowledge about the problem being modelled. The a priori probability of conformity assessment is the initial information in the design of information and measuring systems. It is associated with the parameters of the distribution law of possible values of the object (or its parameters), which depend on the characteristics of the technological process. A measurement procedure, which is known to be error-prone, is used to obtain data on the progress of the process. When measurement errors are insignificant, the state of technological process is reflected by the results of control and measuring operations. In this case, erroneous decisions are absent.

The monograph [3] examines issues related to the influence of systematic additive measurement error, if it does not arise in the production process. When determining the so-called empirical control limits, it is assumed that the presence of a constant error can be considered when calibrating the control charts (CC). When an additive error occurs during working control and measuring operations, this leads to a shift in the distribution law of possible values in relation to the control (normative) values of the characteristic parameter of the technological process. Therefore, erroneous decisions about the disorder of the process may occur.

The first author of this work, Prof. Dr. Ye. T. Volodarskyj, about the 2010 year initiated the research direction covering the development of methods for assessing the reliability and accuracy of the continuous production process control. In this control, measurement systems with different types of control cards are used. Together with metrologists from Ukraine and Poland, are developed a total of over 60 publications using the current statistical approach to measurement errors and their uncertainties. The topics of four these works [10–13] are briefly discussed below.

The criteria for identifying the presence of a measurement error that can occur during process control are examined in the article [12]. Sequences of control points and their locations within the control boundaries were identified, which allows identifying the impact of measurement errors at the initial stage of process upset. The next step in increasing the reliability of process control is to consider the impact of not only the additive but also the multiplicative component of measurement errors during CC calibration.

In works [10, 11, 13] analysed is the probability and nature of erroneous decisions with a real characteristic of measurement transformation. Methods aimed at increasing the reliability of the decisions made are considered.

The a priori probability of erroneous decisions during control is obtained under the assumption that one of the possible events may occur. The use of the approach proposed by Bayes is based on that, the event has already occurred and thereby reduces

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the number of events that could lead to such a result by 2 times. This allows increasing the statistical reliability of decisions made [4, 5].

Considering biased results, correcting decision errors, reproducing the general population and finding the probability of a true positive result are the main advantages of using the Bayesian approach [2]. The Bayesian approach is used to estimate the probabilities of events using additional data from an experiment. It describes a probability of an event based on past (a priori) knowledge of conditions under which an event may occur. The probability of the cause of the event could be calculated based on the information that the event occurred.

1. Possible results of the technological process control

The values of the controlled parameters will differ from the nominal values and will vary from object to object (process) due to production errors and the influence of destabilizing factors that cannot be identified and considered. This means that the values of the controlled parameter that characterize the conformity with the standards are the implementation of a random variable, i.e. the possible values of the controlled parameter [6]. Depending on the use, the characteristic parameter by which the state of the object (process) is determined is subject to limit values x_l and x_u. To determine whether the objects comply or do not comply with the standard, a conformity assessment procedure is carried out [7].

Due to the random errors of the measurement devices, the evaluation of the results can show the suitability or unsuitability of the controlled object (CO) or process for further use. Thus, the article will consider the following elementary events describing possible actual states of the CO and possible control results:

- A – real state of a CO that conforms to the standard,
- B – result of control procedure that CO is suitable.

As shown in the Table 1, there are four possible variants of complex events.

Table 1. Possible variants of complex events

		suitability	
		B	$\overline{B}$
compliance	A	AB	$A\overline{B}$
	$\overline{A}$	$\overline{A}B$	$\overline{AB}$

These events are incompatible in pairs. They form a complete group. The probability of their occurrence is equal to one, i.e.:

$$\sum_{i=1}^{4} P_i = P(A\overline{B}) + P(\overline{A}B) + P(AB) + P(\overline{AB}) = 1 \qquad (1)$$

There are decisions which correspond to the probability:

- $P(AB)$ – the probability of a true state – CO complies with the standards,
- $P(\overline{AB})$ – the probability of a true state – CO does not comply with the standards,
- $P(A\overline{B})$ – the probability of a false alarm,
- $P(\overline{A}B)$ – the probability of an undetected alarm.

Under conditions where mistakes can be made, values of characteristic parameter x are used to assess compliance. The decision on the possibility of using CO for its functional purpose is based on the measuring result z:

$$z = x + y \qquad (2)$$

where: x is the characteristic parameter of the CO; y is the random measurement error (possible values).

Each complex event's probability (Table. 1) is equal to its unconditional likelihood multiplied by its conditional probability, assuming that first event occurs [4]. Consider the plausibility of the result of conformity evaluation "unsuitable" $\overline{B}$. It appears under the circumstances [8] given below.

- The object meets standards A (technological process (TP) is in a controlled state). However, after measurement, the result incorrectly indicates non-compliance with standards, causing a false alarm (failure). The probability of this complex event is written as:

$$P(A\overline{B}) = P(A) \cdot P(\overline{B}/A) \qquad (3)$$

- There are no incorrect decisions: the object does not actually meet the standards, and the evaluation result is not suitable $\overline{B}$, correctly reflects its functional state. The probability of this event is:

$$P(\overline{AB}) = P(\overline{A}) \cdot P(\overline{B}/\overline{A}) \qquad (4)$$

With the help of Bayes' formula, we can calculate the probability (confidence) of the false alarm that the true state is A but the decision has been made $\overline{B}$ is described by the formula [2]:

$$P(A/\overline{B}) = \frac{P(A\overline{B})}{P(A\overline{B}) + P(\overline{AB})} = \frac{P(A) \cdot P(\overline{B}/A)}{P(A) \cdot P(\overline{B}/A) + P(\overline{A}) \cdot P(\overline{B}/\overline{A})} \qquad (5)$$

where: $P(A/\overline{B})$ is the confidence in the obtained result $\overline{B}$ (a posteriori probability of plausibility of the decision on unsuitability); $P(\overline{A})$ is the probability that the object complies with the standard; $P(\overline{B}/A)$ is the conditional probability of deciding on the unsuitability of the CO, while it complies with the standards; $P(A) \cdot P(\overline{B}/A)$ is a priori probability of a false refusal (alarm); $P(\overline{A}) \cdot P(\overline{B}/\overline{A})$ is a priori probability of making the correct decision on the unsuitability of the CO.

The absolute a-priori probability of getting a wrong decision (3) on non-compliance is in the numerator of (5). Denominator is sum of probability of complex events leading to decision $\overline{B}$ unsuitable. Thus, what proportion of the incorrect decision "unsuitable" remains in the accepted decision $\overline{B}$ is indicated by the probability $P(A/\overline{B})$. It is a confidence level.

Control charts are widely used to assess the conformity of a TP to specified/established standards [15]. Provided that the technological process is in a statistically controlled state, the nominal value of the characteristic parameter is assumed when constructing the CC [7]. This value is the centre line CL on the graph. The nominal value is either reproduced or calculated. Relative to CL are the upper UCL and lower LCL limits. These are called *action lines*. These lines are assigned the limit values of the permissible deviation x_l and x_u of the characteristic parameter of the CO from the nominal value, the so-called limits of the tolerance interval. Conformity of the CO with the specified standards is proved by the presence of a characteristic parameter within the tolerance interval [14]:

$$x_l \le x \le x_u \qquad (6)$$

If the process characteristic exceeds the tolerance interval an "alarm signal" will be generated, indicating that the TP has a non-random influence [16]. The above is the way to use the CC. It is necessary to measure the characteristic parameter of the process before applying control points to the CC [9]. The random error y affects the measurement, which is why (2) can be in the nonconformity zone, for example. This leads to a false alarm.

The probabilities of complex events (1), considering the influence of the measurement error (2) and the maximum values of the permissible deviation (6), characterizing the possible states of the CO and the corresponding control results [6]:

- CO meet the standards, and the control result is suitable: $P(AB) = P[(x_l \le x \le x_u) \cap (x_l \le z \le x_u)]$

- CO does not meet the standards and is unsuitable: $P(\overline{AB}) = P[([x < x_l] \cup [x > x_u]) \cap ([z < x_l] \cup [z > x_u])]$
- CO does not meet the standards and is suitable: $P(\overline{A}B) = P[([x < x_l] \cup [x > x_u]) \cap (x_l \le z \le x_u)]$
- CO meets the standards and is unsuitable: $P(A\overline{B}) = P[(x_l \le x \le x_u) \cap ([z < x_l] \cup [z > x_u])]$

The possible situation near the upper control limit x_u (Fig. 1) will be considered in the next part.

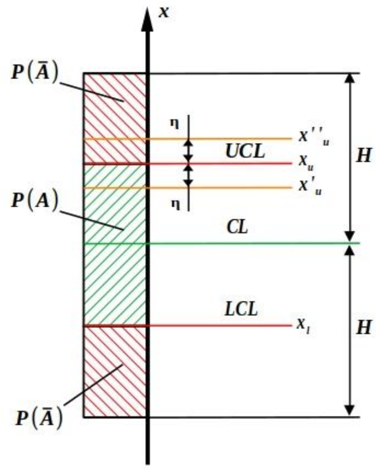

Fig. 1. Introduction of additional control boundaries

2. False alarm event probability

In the case of a false alarm, the value of the characteristic parameter complies with the standards, i.e. relation (6) is fulfilled, but based on the measurement results a decision is made that the CO does not comply with the standards and its probability is

$$P(A\overline{B})_{x_u} = P[(x_l \le x \le x_u) \cap (z > x_u)] \quad (7)$$

Due to the dependence of the measurement result on the CO parameter (2), the events on the right side of expression (7) are dependent. We replace Z in expression (7) with its definition from (2) to use the independent events. The probability of a false alarm is represented by the expression:

$$P(A\overline{B})_{x_u} = P[(x_l \le x \le x_u) \cap (y > x_u - x)] \quad (8)$$

Convolving independent variables was done. The false rejection is caused by the fact that during the measurement the true value of the parameter x, which is in the conforming area, is added to the possible values of the random variable y (measurement error), so that the result z is in the non-conforming area $\overline{B}$. In this case, it is not in conformity with the standards for the fulfillment of the functional purpose. When the characteristic parameter takes the value $x = x_u$, the influence of the measurement error is the greatest. So there is a certain value of η where the effect of the error can be ignored. As a result, the introduction of additional control limits $x''_u = x_u + \eta$ and $x'_u = x_u - \eta$ allows to reduce the volume of control and measurement operations without losing the statistical reliability of the decisions made. The control limits are symmetrical with respect to CC's upper action line UCL, which corresponds to limit x_u (Fig. 1). Fig. 1 also shows that under the condition $x < x'_u$, the probability of false rejection is negligible. It is possible that the measurement result is $z > x_u$, i.e. that a decision on unsuitability can be made, only if $x \ge x'_u$. In this case, the expression (8) takes the form

$$P(A\overline{B})_{x_u} = P[(x_u - \eta \le x \le x_u) \cap (x_u - x < y < +\eta)] \quad (9)$$

The region where the combination of x and y can lead to a false alarm is represented in the orthogonal coordinate system. This region has a right-sloping hatch in Fig. 2. If the distribution is uniform, the false alarm is the region bounded by the bold lines, and we can determine the integration limits using (9):

$$P(A\overline{B})_{x_u} = \int_{x_u-\eta}^{x_u} f(x)dx \int_{x_u-x}^{+\eta} f_1(y)dy \quad (10)$$

where: $f(x)$ is the probability distribution density function of the values of the characteristic parameter of the TP, $f_1(x)$ is the probability distribution density function of the error of measuring instrument.

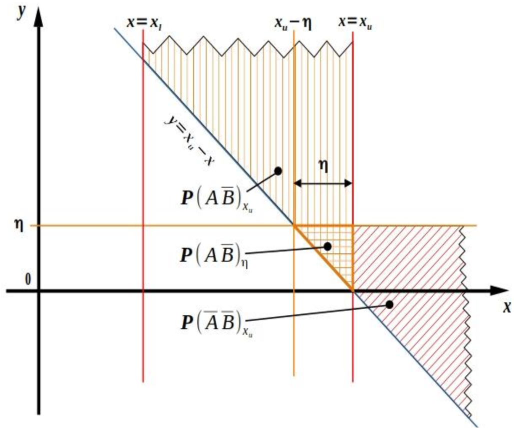

Fig. 2. The integration region of the equation (10)

This corresponds to the second component in the denominator of eq. (5) with the probability represented by the expression:

$$P(\overline{AB}) = P[(x > x_u) \cap (z > x_u)] = \\ = P[(x > x_u) \cap (y > x_u - x)] \quad (11)$$

Thus, the probability of a complex event represented by expression (11), using Fig. 2, can be calculated as:

$$P(\overline{AB})_{x_u} = \int_{x_u}^{+\infty} f(x)dx \int_{x_u-x}^{+\eta} f_1(y)dy \quad (12)$$

3. Undetected alarm event probability

An undetected alarm occurs when the CO does not actually meet the standards $\overline{A}$ but the conformity assessment procedure has decided that the CO is suitable B. However, the result of the assessment B may also occur when the object actually meets the standard A. By analogy with expression (5), we write the Bayes formula for the case where the evaluation result is "suitable":

$$P(\overline{A}/B) = \frac{P(\overline{A}) \cdot P(B/\overline{A})}{P(\overline{A}) \cdot P(B/\overline{A}) + P(A) \cdot P(B/A)} \quad (13)$$

Due to the non-ideal of the measurement procedure, the numerator of expression (13) contains the a priori probability of an undetected alarm. The denominator is the sum of the probabilities of events that can produce an appropriate outcome B when assessing compliance. As before, consider situation at upper bound of x_u. From Fig. 1, we can assume that undetected nonconformity with standards may occur if the value of characteristic x is in the interval $x_u \div x_u''$:

$$P(\overline{A}B)_{x_u} = P[(x > x_u) \cap (x_l \le z \le x_u)] \quad (14)$$

After substituting (2) into (14), we obtain an expression for the convolution of independent events:

$$P(\overline{A}B)_{x_u} = P[(x > x_u) \cap (x_l - x \le y \le x_u - x)]$$

The greatest influence of the measurement error y will be at $x = x_u$, and the error takes on a negative value -η.

Then, to estimate the a-priori probability of an undetected alarm, we have (see Fig. 3)

$$P(\overline{A}B)_{x_u} = P[(x_u < x \le x_u + \eta) \cap (-\eta \le y \le x_u - x)]$$

Based on the region with double hatching shown in Fig. 3, we find integration boundaries for calculating the a priori probability of an undetected alarm

$$P(\overline{A}B)_{x_u} = \int_{x_u}^{x_u+\eta} f(x)\,dx \int_{-\eta}^{x_u-x} f_1(y)dy$$

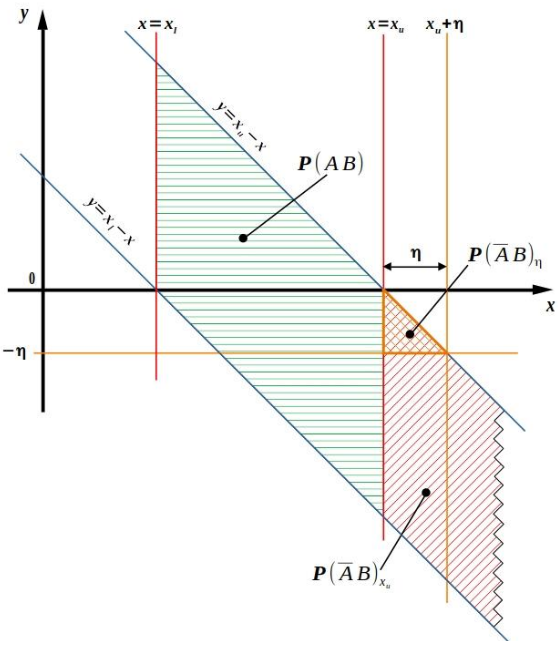

Fig. 3. The integration region of the equation (14)

It is necessary to write an expression that would correspond to the second component of the denominator of expression (13) to check the plausibility of the decision on suitability when evaluating compliance with standards. We have events that are independent

$$P(AB)_{x_u} = P[(x_l \le x \le x_u) \cap (x_l - x \le y \le x_u - x)]$$

Thus, the second component of the denominator of expression (13), which characterizes the prior confidence in the suitable solution B, can be expressed as follows:

$$P(AB)_{x_u} = \int_{x_l}^{x_u} f(x)\,dx \int_{-\eta}^{x_u-x} f_1(y)dy$$

4. False alarm probability with uniform distribution law

Uniform distribution densities of possible values of TP's parameter x and random errors y are

$$f(x) = \frac{1}{2H}, f_1(y) = \frac{1}{2\eta} \tag{15}$$

The set of possible values of the corresponding events is shown on Fig. 4.

The volumes of prisms (16) are the geometric interpretation of the probability of complex events. Their heights are equal. They are the product of the densities of the random variables (17). The bases are the areas of regions defined by these variables (Fig. 4).

$$P_{xy} = LS_{xy} \tag{16}$$

$$L = \frac{1}{4H\eta} \tag{17}$$

The a-priori probability of an erroneous decision on the process non-compliance with the standards based on expression (10) will look like:

$$P(A\overline{B})_{\eta} = \frac{1}{4H\eta}\int_{abc} dx \int_{abc} dy \tag{18}$$

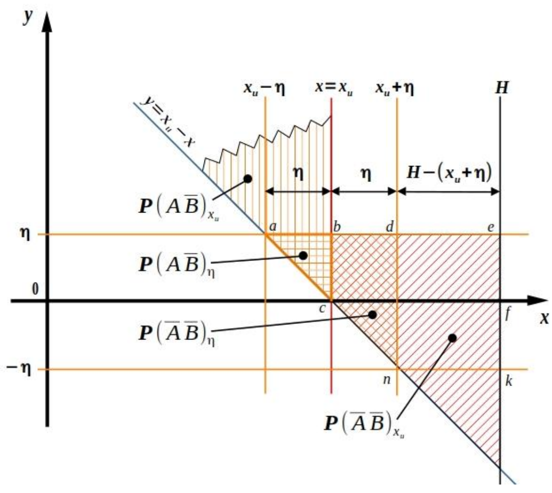

Fig. 4. The range of possible values of x and y

The probability $P(A\overline{B})_{\eta}$ is proportional to the area of equilateral right triangle S_{kad}:

$$P(A\overline{B})_{\eta} = LS_{abc} = \frac{\eta}{8H} \tag{19}$$

The a priori probability of making the correct decision on non-compliance of the technological process with the standards based on (12) will look like:

$$P(\overline{AB})_{\eta} = \frac{1}{4H\eta}\int_{beknc} dx \int_{beknc} dy \tag{20}$$

The probability $P(\overline{AB})_{\eta}$ is proportional to the area S_{beknc}:

$$P(\overline{AB})_{\eta} = LS_{beknc} = \frac{1}{4H\eta}\frac{4\eta H - 4\eta x_u - \eta^2}{2} \tag{21}$$

In Bayes' (18, 20), if the true state of the process is normal, the confidence in the decision that the process does not comply with the standards is given by the expression

$$P(A/\overline{B})_{\eta} = \frac{P(A\overline{B})_{\eta}}{P(A\overline{B})_{\eta} + P(\overline{AB})_{\eta}} \tag{22}$$

The probabilities of complex events correspond to the volume of the prism with the height (17) and the areas of the bases in the case of uniform probability distributions (15) according to Fig. 4. The posteriori probability that the process does not comply with the standards is then given by the expression:

$$P(A/\overline{B})_{\eta} = \frac{LS_{\boldsymbol{kad}}}{LS_{abc} + LS_{beknc}} = \frac{S_{abc}}{S_{abc} + S_{beknc}} \tag{23}$$

We will make it based on the calculation of the areas of the bases of the corresponding prisms (23) in order to determine the plausibility of the erroneous decision on the TP's non-compliance with the norms (22). The areas of the corresponding prism bases (23) are used to calculate the probability of plausibility of a wrong decision on the TP's non-compliance with the standards (22). In this case we get:

$$P(A/\overline{B})_{\eta} = \frac{\eta}{4(H - x_u)} \tag{24}$$

Defining the posterior probability of a false rejection (24) increases the probability of assessing the TP's compliance with the standards. Like any probability, the value (24) corresponds to the condition:

$$0 \le \frac{\eta}{4(H - x_u)} \le 1 \tag{25}$$

Let's consider the extreme cases of conditions (25). In the case $P(A/\overline{B})_{\eta} = 0$, i. e. in the absence of additive random measurement error $\eta = 0$, and therefore in the absence of a false rejection, the posterior probability of making a false decision about the TP's non-compliance with the standards is possible (19).

If $P(A/\overline{B})_\eta = 1$, this means that a wrong decision was made. This means that the probability of the correct decision on the non-compliance of the technological process with the standards is $P(\overline{AB})_\eta = 0$ in the denominator of the expression (22). Put another way, the probability of process disorder asymptotically tends to zero.

Let's consider a numerical example. First, we transform expressions (19), (24), and introduce $d = \frac{\eta}{H}$ and $x_u = aH$, where $a < 1$. Then we obtain the expressions:

$$P(A\overline{B})_\mu = \frac{d}{8} \tag{26}$$

$$P(A/\overline{B})_\mu = \frac{d}{4}\frac{1}{1-a} \tag{27}$$

Let's assume that $d = 0.2$. Then the prior probability will be equal to 2.5% and does not depend on the value of x_u. Let's consider how the posterior probability will change depending on the value of x_u. The results are summarized in Table 2.

Table 2. Dependence of the posterior probability on x_u

	$d = 0.1$	$d = 0.2$
x_u	$P(A/\overline{B})_\mu$ (26)	$P(A/\overline{B})_\mu$ (27)
0.55	5.6	11.1
0.60H	6.3	12.5
0.65H	7.1	14.3
0.70H	8.3	16.7
0.75H	10.0	20.0
0.80H	12.5	25.0

Analysis of the obtained data showed that with an increase in the tolerance interval, with H fixed, the probability $P(A/\overline{B})_\eta$ increases, since $P(\overline{B})_\eta$ decreases, the more plausible a posteriori solution becomes. In the limit, expression (22) asymptotically tends to 1.

5. Summary

This paper discusses how to evaluate process conformance using quantitative control charts, where process characteristics are measured and then compared to a standard. It is shown that measurement errors lead to erroneous decisions, not only false alarms, but also undetected alarms. It is established that a priori decision probabilities, including correct and incorrect decision probabilities, are possible:

- to assess capabilities of a measuring system before using it,
- to put forward requirements for metrological characteristics, under which a given probability of control will be fulfilled.

The Bayesian approach, which is predicated on the solution obtained during the inspection process, yields ancillary information and thereby reduces the uncertainty associated with potential combinations of elementary events by a factor of two.

A priori dependence on the relationship between x_u and the upper possible value of H will increase proportionally with the increase in the reduced error d.

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† Prof. Yevhen T. Volodarskyi
e-mail: vet-1@ukr.net

Prof. Dr. of Tech. Sc. Yevhen T. Volodarskyi worked in National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" (KPI), Department of Experimental Research Automation; Chairman of the Sub-commission "Metrology" at the State Accreditation Agency of Ukraine. Awarded by the President of Ukraine "Honored Lecturer of Ukraine". Author of several books and over 300 publications. Area of scientific interests: theoretical foundations of measurement systems and monitoring and testing systems.
Prof. Y.T. Volodarskyi unexpectedly died on February 9, 2025, still in the full creative power.

https://orcid.org/0000-0003-2573-6543

Ph.D. Oleh Kozyr
e-mail: olegkozyr86@gmail.com

Graduated at National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" (KPI) on M.Sc. degree in 2012. and Ph.D. (Candidate of Technical Sciences) in 2021. Specializing in measurement equipment, standardization, certification. Work: from 2016 at KPI, Department of Information and Measurement Technologies of Instrumental Engineering Faculty, now as docent (assoc. prof.) from 2025. Author or coauthor of 22 papers, 36 proceedings, 7 textbooks, 2 monographs and 5 patents. Research interests: statistical modeling, statistical quality control, machine learning.

https://orcid.org/0000-0002-9285-5940

Ph.D. Zygmunt Lech Warsza
e-mail: zlw1936@gmail.com

Graduate at the Faculty of Electrical Engineering, Warsaw University of Technology in 1959, Ph.D. in 1967, associate professor 1970- 1992.
Work: Institute of Electrical Engineering 1958–1963 and 1994–1995, Warsaw University of Technology 1960–1970, Kielce-Radom University of Technology 1970–1978 (organizer and dean of the Faculty of Transport in Radom), organizer and head of: the Measurement Equipment Center at the Institute of Meteorology and Water Management 1978–1982 and the Department of Automation and Measurements at the Industrial Chemistry Institute 1983–1992. Advisor to the Minister of National Education 1992–1995. Lecturing at Radom University of Technology 1983–2002. Chief specialist at the Industrial Institute of Automation and Measurements PIAP 2010–2023.
Author or co-author of over 460 publications, including several joint monographs and 2 own, several dozen research and design works, 11 patents and promotor (supervisor) of 2 Ph.D. thesis.

https://orcid.org/0000-0002-3537-6134