

MODELING OF A SYSTEM OF QUALITY ASSESSMENT INDICATORS OF MEASURING INSTRUMENTS

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Modern measuring instruments (MI) are of great importance for providing measurements in all areas of the national economy. Their main purpose is to conduct accurate and reliable measurements in order to obtain complete and reliable measurement information. To perform this important function, MI must be of appropriate quality, which must be reliably assessed.

In the traditional definition, MI is a technical means that is used in measurements and has standardized characteristics. For technical means, there is a traditional system of quality indicators. In addition to these quality indicators, additional specific indicators should be established for MI, which should objectively assess the metrological characteristics.

The expediency of creating and using a special system of quality indicators for all stages of the MI life cycle is proved. Building such a system requires maximum use of quantitative characteristics that express certain quality indicators. Important indicators of this system are a number of MI indicators related to metrological characteristics. For MI, it is also advisable to use a common system of quality indicators for technical facilities.

The proposed multiple models of MI quality indicators and evaluation of MI quality indicators allow studying the influence of MI quality indicators and performing their evaluation at all stages of the MI life cycle. Understanding and managing the system for evaluating MI quality indicators helps to increase efficiency in achieving planned results. For effective implementation of these models, it is necessary to use regulated requirements of some international and regional standards and recommendations

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1. Introduction

The international standard ISO 9000 [1] establishes the general concept of product quality as the ability to satisfy its customers. Product quality covers not only intended functions and characteristics, but also benefits to the customer. At the same time, the standard regulates a more specific definition of quality as the degree to which the set of object characteristics meets the requirements. Quality level is also defined as a category or rank assigned to different requirements of objects that have the same functional application. As an indicator of activity, a measurable result is established, and as a characteristic of an object – a distinctive feature, which can be both qualitative and quantitative. Metrological characteristic is defined as a characteristic that can affect the measurement result. It is unique to a measuring instru-

ment (MI) and can be considered one of the most important indicators of MI.

Product quality, in particular MI, is the basis of its competitiveness. Traditionally, product quality is a set of properties that determine its suitability to meet the stipulated and expected needs in accordance with its purpose. Product property is an objective feature of a product that is manifested in its development, design, manufacture, operation and intended use. To objectively assess product quality, its properties are characterized quantitatively and qualitatively. Quantitative characterization of one or more product properties that make up its quality is traditionally called the product quality indicator (PQI) [2–5].

Requirements for modern quality management systems are regulated by the international standard ISO 9001 [6]. In general, this standard aims to create opportunities to

increase customer satisfaction and to take into account risks associated with the organization's activities. One of the principles of quality management is to make decisions based on factual data, as well as to improve the organization's processes based on the evaluation of data and information. To verify the compliance of products with the established requirements, it is necessary to determine the resources needed to ensure reliable results. If measurement traceability (metrological traceability) is a requirement or an essential element of guaranteeing confidence in the reliability of measurement results, then special requirements are set for the state of MI.

The international standard ISO 10012 [7] establishes general requirements and contains guidelines for managing the processes of measurement and metrological confirmation of MI suitability. Metrological confirmation means a set of operations to ensure that the MI meets metrological requirements for its intended use. Metrological confirmation generally covers calibration and verification, which are designed to establish the metrological characteristics of the MI. Metrological characteristic in this standard means a characteristic feature that may affect the measurement result. MI, as a rule, can have several metrological characteristics.

The international standard ISO/IEC 17025 [8] contains a special section on metrological traceability. Its definition in this standard corresponds to the ISO/IEC Guide 99 international vocabulary [9]. Metrological traceability is a property of the measurement result, and the concept of measurement uncertainty is used for it [9, 10]. There are various options for ensuring metrological traceability, but one of the main ones is the calibration of MI. All this emphasizes the peculiarity of MI as a technical means.

Summarizing the requirements of the considered international standards, we can state the great importance of modern MI for all areas of the national economy. Their main purpose is to conduct accurate and reliable measurements in order to obtain complete and reliable measurement information. To perform this important function, MI must be of proper quality, which must be reliably assessed. In the traditional definition, MI is a technical means that is used in measurements and has normalized characteristics.

For technical means, there is a traditional system of quality indicators. A number of these quality indicators are common to MI, but it is impossible to draw conclusions about the MI quality on their basis alone. If based only on the traditional system of quality indicators, the result of MI evaluation may be distorted. Therefore, research related to determining individual or a special system of MI-specific indicators is relevant. However, for reliable assessment of MI quality, other "traditional" quality indicators of technical means cannot be discarded, in particular, manufacturability, design, functionality, standardization and unification, ergonomic, aesthetic, economic.

2. Literature review and problem statement

Almost all modern MI are complex hardware and software systems, mainly using modern software. MI are characterized by various purposes, areas of application, complexity of implementation, life cycle duration, etc. It can be stated that their quality is laid down at the design stage and implemented at the production stage. Therefore, these stages should be considered the main ones for the MI life cycle.

In [2], general issues concerning innovative mechanisms for ensuring the competitiveness of goods in the development are considered, in [3] – the concept of product quality and stages of evolution, in [4] – evolution of quality management. However, these works do not consider any specific indicators of product quality. In [5], a general grouping of various product characteristics and some quality indicators is proposed, however, their features and spheres are not considered. In [11], the main attention is paid to the issues of quality management of production and service, in [12] – quality management of products and services. However, these works do not consider any specific indicators of product quality.

Current strategies for monitoring quality processes are mainly focused on one specific quality indicator. For several related quality indicators, traditional algorithms establish the same characteristics, ignoring the specific features of each indicator. Due to the correlation between quality indicators, important information can be obtained on common grounds. In [13], a multivalued quality model is proposed for joint monitoring of quality indicators. This model finds a correlation among different quality indicators. However, this model is general and does not take into account the specifics of MI quality indicators.

The chosen product quality indicator can greatly affect the overall result of quality assessment. In [14], a comparison of several different quality indicators was made to get a better idea of their characteristics and impact on the overall result. It was shown that quality indicators with the same goals gave contradictory and significantly different results. Therefore, none of the quality indicators can have an advantage over the other. However, this work is also general and also does not take into account the specifics of MI quality indicators.

In [15], the indicators of quality and life cycle of protected information and measuring systems are considered in general, in [16] – indicators of quality and life cycle of information and measuring systems. However, these works do not provide any details of quality indicators. In [17], the issues of testing MI software at the national level are considered, in [18] – testing of MI software for conformity assessment. These papers detail MI software indicators to be evaluated and consider only one group of MI quality indicators related to the software part. These indicators can be only a subsystem of quality indicators of the general system of MI quality indicators.

In [19], the algorithm for assessing the individual metrological reliability of MI is considered in detail, in [20] – the development of a system for ensuring the metrological reliability of MI. This is only one, although important, quality indicator of MI – metrological reliability. This indicator can be included in the system of specific indicators of MI quality.

The analysis showed the urgent need to consider some specific indicators of MI quality as elements of a special system of MI quality indicators. The creation of such a system of MI indicators will increase the reliability of assessing the MI quality taking into account all the essential MI quality components.

3. The aim and objectives of the study

The aim of the study is to consider the basis for creating a special system of MI quality indicators. This system should

be based on both the traditional system of quality indicators of technical means and MI-specific indicators. To achieve the aim, it is necessary to perform the task of mathematical modeling of the system of these indicators.

To achieve the aim, the following objectives were set:

- to explore the possibilities and features of creating a special system of MI quality indicators;
- to carry out mathematical modeling of the system of MI quality indicators, which would cover all stages of the MI life cycle;
- to carry out mathematical modeling of evaluation of MI quality indicators at all stages of the MI life cycle.

4. Materials and methods of studying quality indicators of measuring instruments

To objectively assess the quality of a product, it is necessary to characterize its properties. Property is the objective ability of a product, which is manifested in its creation, operation or consumption. For this purpose, special quality indicators and signs of products are used. Moreover, when describing product properties, the features are used only if they characterize quite significant properties and cannot be given in the form of an indicator (i.e. in a numerical form). Product quality is characterized by several indicators and a certain weighted sum of values of individual characteristics.

Quantitative reproduction of product properties is characterized by PQI, which are generally divided into functional, resource-saving, environmental.

Functional PQI include indicators that reflect consumer properties of products, such as:

- technical effect (performance, power, speed, operating speed, etc.); reliability (durability);
- ergonomics (fulfillment of hygienic, anthropological, physiological requirements);
- aesthetics.

PQI are always considered in accordance with certain conditions of the product life cycle. When assessing the level of quality, both technical and economic indicators are used. The choice of PQI establishes a list of quantitative characteristics of product properties, which determine its quality and provide an assessment of the level of product quality. An appropriate range of indicators should be used to objectively assess the level of product quality. No PQI can be the only one to substantiate the conclusions of product evaluation. In general, PQI for the stages of the product life cycle can be divided as follows: quality indicators of consumer properties of products; indicators of manufacturing quality of products; indicators of operational qualities of products.

PQI can be classified on various grounds:

- content;
- method of numerical expression (absolute, relative, specific);
- degree of differentiation (single, complex, integral);
- characteristic properties (discrete, continuous);
- stages of life cycle (forecast, design, production, operation);
- quality assessment (basic and relative).

For modern technology, all possible groups of PQI lose their significance if a sample of this technique is unreliable. The main types of PQI are shown in Table 1.

Table 1

Main types of product quality indicators

Classification feature	Indicators
Relation to product properties	Purpose, reliability, manufacturability, ergonomics, aesthetics, standardization, patent law, economic
Significance for quality assessment	Basic and additional
Number of properties indicated	Single and complex
Stage of determination	Forecast, design, production, operational
Methods of determination	Instrumental, computational, statistical, expert, etc.
Dimension of indicated values	Absolute, given, dimensionless

Different PQI can be compared with each other, while others act only independently and do not intersect with any others. Depending on the type and kind of industrial products, the system of quality indicators can differ significantly. PQI values can be formed on the basis of: calculated (forecast) indicators; values recommended by reputable organizations; best values in the world or national practice; standards or regulations.

5. Results of mathematical modeling of quality indicators of the measuring instrument

5.1. Research of the possibility and features of creating a system of quality indicators for the measuring instrument

For technical facilities, structural PQI should be considered simultaneously with such indicators as structure and properties, technical excellence, reliability, durability, safety, maintainability, applicability, repeatability, etc. Production indicators can be used in conjunction with design, technical excellence, reliability, durability, safety, maintainability, structural strength, repeatability, etc.

The model of the product life cycle, or the so-called quality loop, is based on the analysis of the main stages of formation and change of PQI. The basis of the model is a chain of successive activities, the quality of which is reflected in the PQI. The quality of MI is planned and formed in the production sphere and is subject to changes in the consumer sphere (Fig. 1). MI characteristics can be changed by affecting the components of the quality loop [21].

The quality loop is a conceptual model of interdependent activities that affect the quality at different stages: from identifying needs to assessing their satisfaction. In this model, the quality system is the object of management at all stages of the production process (Fig. 1). The quality loop clearly shows the consistent reflection of the quality of processes on the quality of the final result at the stages of the MI life cycle. The generalized quality of the result is a set of design, production and operational quality (Fig. 2).

The PQI system can be developed based on the following principles:

- use of essential requirements of technical regulations and normative documents (standards);
- maximum use of quantitative characteristics that express certain PQI;
- use of a quality feature only in cases when an important quality feature cannot be interpreted in the PQI;
- grouping and systematization of PQI.

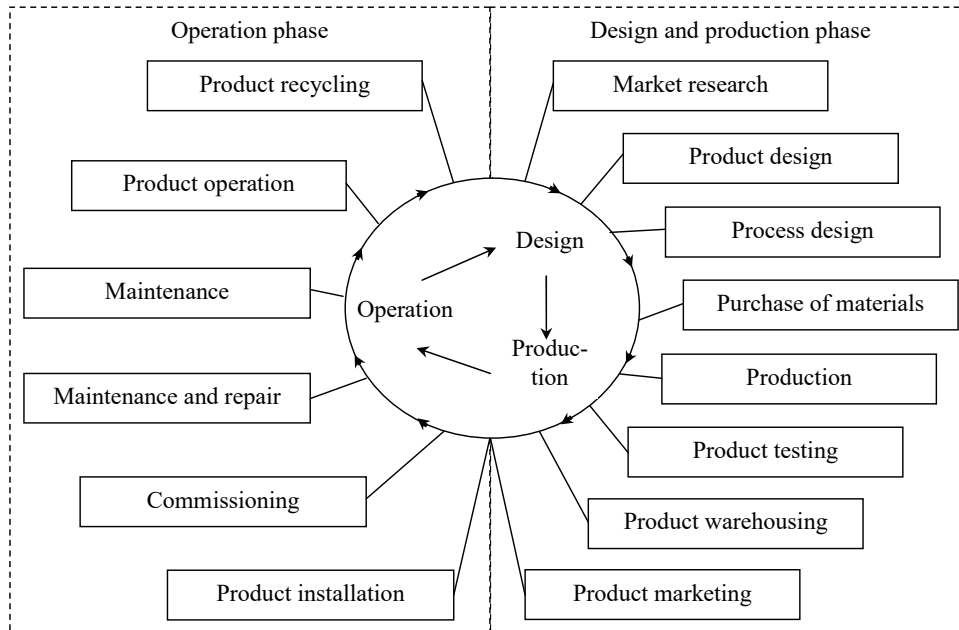


Fig. 1. Product quality loop for the measuring instrument life cycle

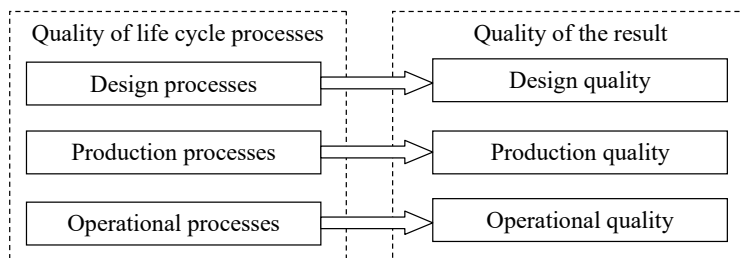


Fig. 2. Display of product life cycle processes on the quality of the result

The following main groups of PQI can be used:

- *purpose* – characterize the properties of products, which determine the main functions they are intended for and determine the scope of their application;
- *reliability* – characterize the ability of products to maintain performance under certain operating and maintenance conditions (express the properties of reliability, durability, maintainability, storage);
- *manufacturability* – characterize the effectiveness of design and technological solutions in ensuring high labor productivity at the stages of manufacture, operation and repair;
- *structural* – characterize the design features of the product (type of structure, type of control system, type of management system, circuit solutions, overall and connecting dimensions, etc.);
- *functional suitability* – characterize the resistance, stability (unit, device or system), technical capabilities of the product;
- *standardization and unification* – provide a rational reduction in the number of standard sizes of components in the designed product (saturation of these products with standard, borrowed and purchased parts or components);
- *ergonomic* – characterize the adaptability of products to anthropometric, physiological, psychophysiological and psychological consumer properties;

- *aesthetic* – relate to the ability of the product to express beauty in an object-sensory form (integrity of composition, rationality of the form, preservation of appearance, perfection of production, artistic expressiveness, etc.);

- *economic* – reflect the costs of development, manufacture and operation of products, etc.

For a particular type of product, the range of quality indicators may be much smaller. It should be noted that the group of purpose indicators is specific to each type of product, so these indicators need special identification or refinement. This also applies to MI, so these indicators should be given special attention.

Important for technical systems (objects) can include a group of reliability indicators. Thus, reliability indicators can be expressed in the absolute value of the product's operating time in hours before the failure and in the form of relative statistical indicators. All operational failures of the product may occur during bench tests, operation, maintenance and inspections.

Durability indicators characterize, in particular:

- initial product life before the first overhaul;
- assigned life;
- service life;
- maximum continuous operation time;
- maximum product life, etc.

In terms of the number of properties disclosed, PQI can be single (relating to only one property) or complex (relating to several properties). Relative PQI is the ratio of a single PQI to the basic PQI expressed in relative units or percentages. The basic indicator is the PQI adopted as a standard in the comparative assessment of product quality. Complex PQI allows characterizing product quality as a whole or a whole group of properties. When calculating these indicators, various methods of quality assessment are used.

A typical algorithm for calculating complex PQI is as follows:

- definition of the PQI nomenclature and construction of their block diagram;
- determination of PQI weighting factors;
- calculation of relative PQI;
- selecting the type of functional dependence;
- calculation of complex PQI.

To determine the nomenclature of complex PQI, weighting factors of PQI, type of functional dependence, expert methods are mainly used.

There are the following types of complex PQI:

- *group* – an indicator that characterizes a group of object properties or properties of a group of objects that are part of the system;

– *integrated* – an indicator that reflects the ratio of the total useful effect of the operation or consumption of products in physical units to the total cost of purchasing and using this product for its intended purpose;

– *generalized* – an indicator that refers to such a set of essential properties of the object, which is used to assess the quality as a whole, etc.

The generalized complex PQI can be an integral or any other complex indicator (for example, a weighted arithmetic or geometric indicator).

The generalized classification of the system of estimating PQI is shown in Fig. 3. It focuses on functional indicators.

In Fig. 3, purpose indicators are only indicated, as they are specific to each type of products, so these indicators require special consideration and analysis.

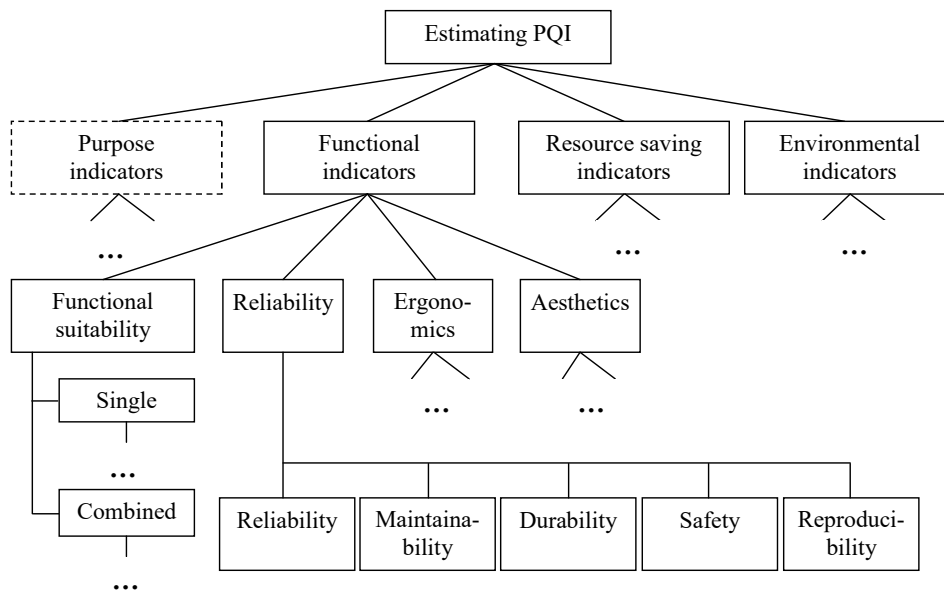


Fig. 3. Generalized classification of the system of estimating product quality indicators

Functional indicators for MI should be supplemented with such indicators as metrological reliability, metrological serviceability, metrological failure, intercalibration interval. These indicators are unique to MI and their study is given in [19, 20, 22–24].

Metrological reliability is the reliability of MI in terms of maintaining metrological serviceability, i.e. the state of MI, which determines the compliance of metrological characteristics of MI with the established requirements. Metrological serviceability is a state of MI in which all standardized metrological characteristics meet the established requirements. Metrological failure is the deviation of metrological characteristics of MI from normalized limits. These two indicators are related.

The main characteristics that can be used to calculate the metrological reliability are as follows:

- probability of trouble-free operation;
- operating time before the first metrological failure;
- average operating time before the first metrological failure;
- rate of metrological failures.

The intercalibration interval is the time interval or operating time between two consecutive MI calibrations. The intercalibration interval is the period of time or operating time between two consecutive MI calibrations, during which

the metrological characteristics of such a tool must meet the established requirements. Determining or changing the intercalibration intervals of MI is a set of mathematical and statistical processes that require accurate and complete data obtained during MI calibration.

These functional indicators of MI are formed or confirmed mainly during the operation phase of the MI life cycle.

The study of possible purpose indicators of MI to create a special system of MI indicators showed the following. The main metrological characteristics of MI should be mainly the purpose indicators of MI.

In general, purpose indicators can be the following metrological characteristics of MI [9]:

- indication interval;
- nominal indication interval (nominal interval);
- range of a nominal indication interval;
- measuring interval or measuring range;
- accuracy class;
- maximum permissible error;
- response time;
- rated operating conditions;
- limiting operation conditions;
- sensitivity of a measuring system;
- discrimination threshold;
- dead band;
- selectivity of a measuring system;
- resolution of a displaying device;
- stability of a measuring instrument;
- instability of a measuring instrument;
- instrument drift;
- step response time.

The group of purpose indicators for the indication of MI has the following definitions [9] and features:

- *indication interval* – a set of values, limited by the most possible indicators (smallest and largest values of quantities);
- *nominal interval* – a set of values, limited to rounded or approximate extreme indicators, achievable with individual MI parameters and used to determine this set;
- *range of a nominal indication interval* – the absolute value of the difference between the extreme values of the nominal indication interval;
- *response time* – the time interval from the start of the input signal to the moment when the indicator reaches and remains within certain limits around the set value.

The group of purpose indicators for the measurement range and accuracy of MI has the following definitions [9] and features:

- *measuring interval* – a set of values of quantities of one type that can be measured by a certain MI together with a given instrumental uncertainty under certain conditions;
- *accuracy class* – MI class that meets the established metrological requirements (measurement errors or instrumental uncertainties within the specified limits in the relevant operating conditions);

– *maximum permissible error* – the extreme value of measurement error in relation to the known reference value of the quantity allowed by the technical conditions of MI.

The group of purpose indicators for MI measurement conditions has the following definitions [9] and features:

– *rated operating conditions* – application conditions that must be met during the measurement to use MI for its intended purpose;

– *limiting operation conditions* – emergency conditions that the MI must withstand without damage and without deterioration of the established metrological characteristics, if it is subsequently used in the rated operating conditions.

The group of purpose indicators for the sensitivity and selectivity of MI has the following definitions [9] and features:

– *sensitivity* – the share of changes in the MI indicators and the corresponding changes in the value of the measured quantity;

– *discrimination threshold* – the largest change in the value of the measured quantity, which does not cause a noticeable change in the corresponding indicator;

– *dead band* – the maximum range within which the value of the measured quantity can change in both directions without causing any changes in the corresponding indicator;

– *selectivity* – a property of the MI applied to a regulated measurement procedure, whereby it provides such measured values for one or more measured quantities that the values of each measured quantity are independent;

– *resolution of a displaying device* – the smallest difference between the indicators of the instrument, which can differ significantly.

The group of purpose indicators for the stability and transient characteristics of MI has the following definitions [9] and features:

– *stability* – the property of the MI to keep constant its metrological characteristics over time;

– *instability* – changes in the metrological characteristics of the MI for the established time interval;

– *instrument drift* – continuous or variable, constantly increasing over time, in the indicator as a result of changes in the metrological properties of the MI;

– *step response time* – the duration between the moment when the input value of the MI is subject to a sudden change between two set constant values of the quantity and the moment when the corresponding indicator is set within the specified limits around its final constant value.

Although this list of MI purpose indicators is quite exhaustive, additional indicators may be established for some MI categories (groups). This may be due, in particular, to the provided operating conditions of MI.

MI purpose indicators are formed at the design stage of the MI life cycle and are established or confirmed at the production phase of the MI life cycle.

5. 2. General mathematical model of the system of quality indicators for the measuring instrument

Modern MI are complex technical systems that are characterized by a set of quality indicators. These quality indicators are based on certain quality properties of a certain MI. The values of quality properties are defined as a measurement function of quality metrics elements (QME). QME

are defined in terms of a property using certain measurement methods, including mathematical transformation to quantify the value of that property. The quality indicator of one property is called a simple quality metric (SQM), and the quality indicator that combines several simple indicators is called a complex quality metric (CQM) [15, 16].

The mathematical model for assessing MI quality can be given in general:

$$QM_{MI} = f \left(\begin{matrix} f(\{(Par, Met), B\}), f(\{QME, B\}), \\ f(\{SQM, B\}), f\{CQM, B\} \end{matrix} \right), \tag{1}$$

where QM_{MI} is the MI CQM (root tree of quality indicators);

CQM is the set of MI CQM of a certain level (sets of nodes of levels of sub-characteristics and characteristics of a tree of quality indicators) $CQM=f(\{SQM, B\})$

$$\begin{cases} CQM_{r_{(|l|-2)}} = f(\{SQM, B\}), \\ CQM_{r_{(|l|-3)}} = f\left(\left\{CQM_{r_{(|l|-2)}}\right\}, B\right), \\ \dots \\ CQM_{r_1} = f\left(\left\{CQM_{r_2}\right\}, B\right); \end{cases}$$

SQM is the set of SQM (set of nodes of the level of properties) $SQM=f(\{QME, B\})$;

QME is the set of elements of quality indicators (set of measurement level) $QME=f(\{Par, Met\}, B)$;

(Par, Met) is the set of measurement tuples (parameters and methods);

$B = \{b_1, \dots, b_i, \dots, b_{|Q_i|}\}$ is the characteristic vector of the

corresponding sets $\left(Q_r \subset Q_{r-1} \mid \forall Q_r \in Q_i, b_i = 1\right)$;

Q_r is the set of quality indicators of level l ($l=(1|l)$ is the level index, $|l|$ is the lower level);

$(|l|-1), (1:|l|-2)$ are the levels of SQM and CQM, respectively;

r is the index of the quality indicator at the corresponding level.

The structure of the model of MI quality indicators is shown in Fig. 4.

Fig. 4 shows k CQM of the level of characteristics, m SQM of the levels of properties and n QME of the measurement level for each SQM.

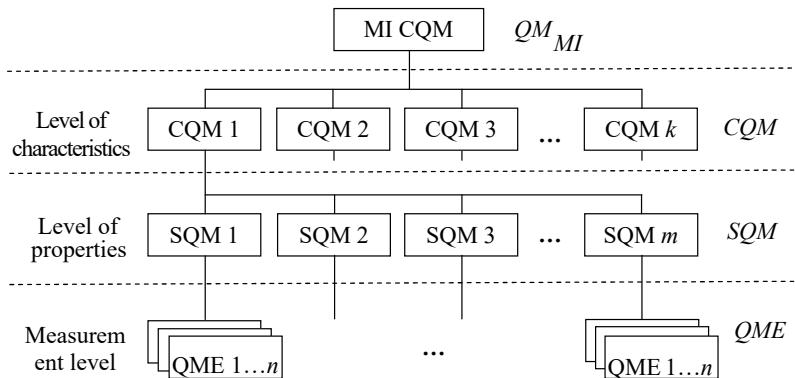


Fig. 4. Structure of the model of measuring instrument quality indicators

5.3. Mathematical model for evaluating quality indicators at the stages of the measuring instrument life cycle

The mathematical model for evaluating quality indicators at the stages of the MI life cycle can be given in general:

$$QM_{MLC} = f(\{PhLC_{QM}\}), \quad (2)$$

where $PhLC_{QM}$ is the MI CQM of the generalized phase of a certain model of quality indicators of the life cycle, which, in turn, is equal to:

$$PhLC_{QM} = f\left(\begin{matrix} VerQM, ValQM, \\ LC_{PrQM}, LC_{SSQM} \end{matrix}\right),$$

where $VerQM$ is the CQM of phase verification;

$ValQM$ is the CQM of phase approval;

LC_{PrQM} is the CQM of phase processes;

LC_{SSQM} is the CQM of subsystems related to the phase (lower-level subsystems).

CQM of phase verification and approval are determined accordingly:

$$VerQM = f\left(\begin{matrix} f(\{(Par, Met), B\}_{Ver}), f(\{QME, B\}_{Ver}), \\ f(\{SQM, B\}_{Ver}), f(\{CQM, B\}_{Ver}) \end{matrix}\right), \quad (4)$$

$$ValQM = f\left(\begin{matrix} f(\{(Par, Met), B\}_{Val}), f(\{QME, B\}_{Val}), \\ f(\{SQM, B\}_{Val}), f(\{CQM, B\}_{Val}) \end{matrix}\right). \quad (5)$$

CQM of phase processes is defined as:

$$LC_{PrQM} = \bigcup_b \{PrLCQ_b\}, \quad (6)$$

where b is the process phase index.

After some generalizations, we get:

$$LC_{PrQM} = f(\{PrLC_{QM}\}),$$

$$PrLC_{QM} = f((VerQM), (ValQM)). \quad (7)$$

The structure of the model for evaluating the quality indicators of the MI life cycle, taking into account expressions (1)–(7) is shown in Fig. 5 ($LC_{PrQM}=\emptyset$, $PrLC_{PrQM}=\emptyset$, $VerQM=\emptyset$, $ValQM=\emptyset$).

In the j -th phase of the MI life cycle, verification is performed for the sets of CQM, SQM and QME for certain processes of the model of quality indicators, and validation – only for the set of CQM of the MI test process after production.

The multiple model for evaluating quality indicators at the stages of the MI life cycle will take the following general form:

$$QM_{MLC} = \left\{ \begin{matrix} \left\{ \bigcup_c \left\{ \bigcup_d \{VerQM_{abcd}, ValQM_{abcd}\} \right\}, \{VerQM_{ab}, ValQM_{ab}\} \right\}, \\ \left\{ \bigcup_{g=2}^a \left\{ \bigcup_b \left\{ \bigcup_c \left\{ \bigcup_d \{VerQM_{abcd}, ValQM_{abcd}\} \right\}, \{VerQM_{ab}, ValQM_{ab}\} \right\}, \dots, \right. \right. \\ \left. \left. \left\{ \bigcup_{|s|} \left\{ \bigcup_b \left\{ \bigcup_c \left\{ \bigcup_d \{VerQM_{abcd}, ValQM_{abcd}\} \right\}, \{VerQM_{ab}, ValQM_{ab}\} \right\} \right\} \right\} \right\} \right\}, \quad (8)$$

where

$$VerQM_z = \left\{ CQM_{z_1} \dots CQM_{z_{(|z|-2)}} \left\{ SQM_{z_{(|z|-1)}} \left\{ QME_{z_{|z|}} \left\{ (Par, Met)_{z_{pp}} \right\} \right\} \right\} \right\},$$

is the set of quality indicators of the verification process;

$$ValQM_z = \left\{ CQM_{z_1} \dots CQM_{z_{(|z|-2)}} \left\{ SQM_{z_{(|z|-1)}} \left\{ QME_{z_{|z|}} \left\{ (Par, Met)_{z_{pp}} \right\} \right\} \right\} \right\},$$

is the set of quality indicators of the approval process;

b, c, d, g are the indices of the MI life cycle phase, MI life cycle phase process, process phase, level, respectively;

z is the index of verification and approval processes at the stages of the MI life cycle;

p is the tuple index of the set of measurement parameters and methods $p=(1:|p|)$.

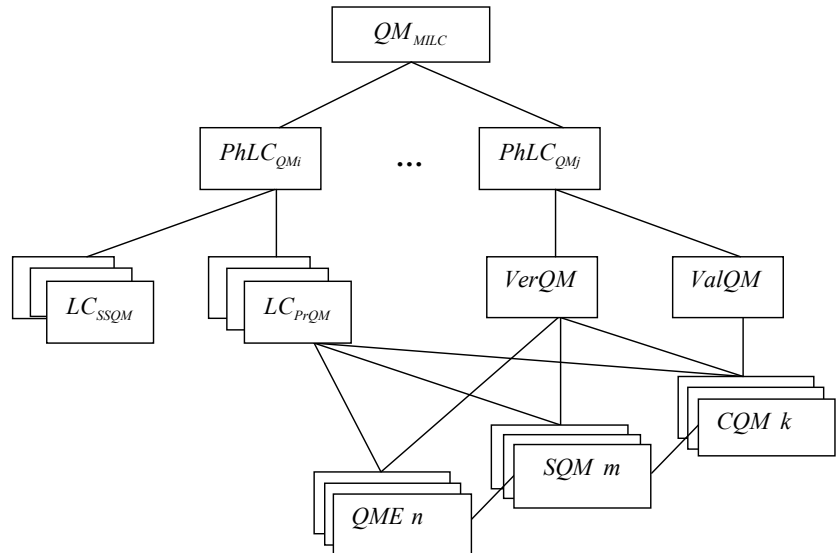


Fig. 5. Structure of the model for evaluating the quality indicators of the measuring instrument life cycle

The set of tree nodes for expression (8) are the sets of CQM and SQM of MI life cycle components, leaves – QME. Hierar-

chical levels correspond to the tree tiers, the and branches are the set of binary relationships between the nodes:

$$Q_r \subset Q_{(r-1)} \mid \forall Q_r \in Q, b_i = 1, \tag{9}$$

where Q_r is the arbitrary quality indicator of the level l (r is the index of the quality indicator at this level);

$$B = \left\{ b_1, b_2, \dots, b_{|Q_r|} \right\}$$

is the characteristic vector $Q_{(r-1)}$, $i = \left(1: |Q_r| \right)$.

The binary relationships between the QME set and measurement parameters and methods are as follows:

$$(Par, Met)_{\mathbb{P}} \subset QME_{\mathbb{P}} \mid b_i = 1, \tag{10}$$

where $B = \left\{ b_1, b_2, \dots, b_{|p|} \right\}$ is the characteristic vector $QME_{\mathbb{P}}$, $i = (1: |p|)$.

Expressions for the multiple model for evaluating quality indicators at the stages of the MI life cycle are the basis for building a tree of quality indicators for the MI system.

6. Discussion of the results of constructing models for evaluating the quality indicators of measuring instruments

The studies have shown that certain quality indicators of the existing traditional system for technical means are common to MI. This applies to manufacturability, design, functionality, standardization and unification, ergonomic, aesthetic and economic indicators. These indicators apply to all stages of the MI life cycle. At the same time, it is not possible to draw conclusions about the MI quality on the basis of these quality indicators alone. The MI-specific quality indicators include all purpose indicators and additional functional indicators (metrological reliability, metrological serviceability, metrological failure, intercalibration interval). Without taking these indicators into account, the result of MI evaluation may be distorted.

The issue of evaluating functional indicators of MI is covered by a number of standards and recommendations. The ISO 9001 standard [6] requires calibration of MI at specific intervals or before use if necessary to ensure the reliability of the results. According to ISO 10012 [7], the methods used to determine or change the frequency of metrological confirmation should be specified in documented methods. This frequency must be constantly analyzed. The ISO/IEC 17025 standard [8] states that the degree of calibration obligatoriness depends on the contribution of calibration uncertainty to the overall test uncertainty. If calibration is the dominant factor, the MI should be calibrated to assess this effect. All this emphasizes the importance of such a MI quality indicator as the intercalibration interval.

The International Guideline [25] provides laboratories with guidelines on methods for determining intercalibration

intervals. The guideline identifies and describes the available and known methods used to estimate intercalibration intervals. Regional recommendations [26] contain methods for determining intercalibration intervals, based on the assumption of continuous (with a finite random rate) changes in the metrological characteristics of MI during operation or storage. They define the criteria for setting these intervals and the algorithm for calculating them. They also provide recommendations on methods for calculating the initial value of this interval and methods for adjusting the interval during the MI operation. It should be noted that the proposed calculation methods are based on the use of metrological reliability indicators.

Many factors affect the intercalibration interval, among which the most important are the following [26]:

- MI category and manufacturer’s recommendations;
- required measurement uncertainty;
- risk of exceeding the maximum permissible error of MI during application;
- tendency to wear and drift;
- operating conditions and environment;
- data obtained from previous calibration reports;
- frequency and quality of intermediate checks between calibrations;
- qualification of service personnel, etc.

In addition to regulations on intercalibration intervals, there have been many works recently on the calculation of this interval by various methods. In particular, in [23], a method for estimating the intercalibration intervals of MI on the basis of reliability indicators is proposed. This technique makes it possible to calculate such intervals using both the confidence limits of errors and the standard deviation of the calibration characteristic of MI. [24] proposes a method for determining intercalibration intervals based on the data of calibration and intermediate verification of MI between calibrations.

The issue of evaluating the purpose indicators of MI has a long-standing, well-established basis and does not require further discussion. The most important is their use in a system with other quality indicators of technical facilities, which also have a well-established basis. The advantage of the conducted researches is that the whole system of indicators necessary for full quality estimation of MI is determined.

A multiple model of MI quality indicators of all stages of the MI life cycle is proposed. The value of MI quality properties is defined as a measurement function of QME. The quality indicator of one MI property is SQM, and the quality indicator that combines several SQMs is CQM. In general, expression (1) establishes a mathematical model for assessing MI quality, and the general structure of the model of MI quality indicators is shown in Fig. 4.

A multiple model of MI quality indicators is proposed, which allows studying the influence of MI quality indicators and performing their evaluation at all stages of the MI life cycle. The structure of the model for evaluating the quality indicators of the MI life cycle is shown in Fig. 5. At a certain phase of the MI life cycle, verification is performed for the sets of CQM, SQM and QME for certain processes of the model of quality indicators, and validation – only for the set of CQM of the MI test process after production. In general, expression (8) establishes a multiple model for evaluating quality indicators at the stages of the MI life cycle. Understanding and managing the system for evaluating MI quality

indicators helps to increase efficiency in achieving planned results. For effective implementation of these models, it is necessary to use regulated requirements of some international and regional standards and recommendations.

The presented studies are the first attempt to present a complex system of MI quality indicators. The established system of MI purpose indicators, as well as additional functional indicators for MI, is not exclusive. Further studies of the system of MI quality indicators can be developed for certain MI categories. This may also be related, in particular, to the provided operating conditions of MI.

7. Conclusions

1. The expediency of using a special system of MI quality indicators is proved. Important indicators of this special system are a number of MI indicators related to both functional and purpose indicators (metrological characteristics). For MI, it is also advisable to use a common system of quality indicators for technical facilities.

2. The conducted mathematical modeling allowed developing a multiple model of the system of MI quality indicators, which covers all stages of the MI life cycle. Additional functional indicators of MI for general technical systems include metrological reliability, metrological serviceability, metrological failure, intercalibration interval. The purpose indicators set for MI are certain metrological characteristics. This allows us to study the impact of MI quality indicators at all stages of the MI life cycle and perform process quality management at all these stages.

3. The conducted mathematical modeling allowed developing a multiple model for evaluating MI quality indicators, which covers all stages of the MI life cycle. Evaluation of additional functional indicators of MI for general technical systems is carried out during the operation phase of the MI life cycle. Assessment of MI purpose indicators is carried out at the design phase of the MI life cycle, and verification of these indicators is carried out at the production phase of the MI life cycle. This allows assessing the importance of MI quality indicators and their components throughout the MI life cycle.

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