Розроблено методику кількісного оцінювання процесів системи управління якістю підприємств, яка включає процедуру отримання їх оцінок на безрозмірній шкалі. В якості залежностей пропонується використовувати порядкові статистики, які враховують максимально-допустиме, мінімально-допустиме та його найкраще (оптимальне) значення. Пропонується оцінювати системи управління якістю на етапі функціонування через оцінки взаємопов'язаних процесів, застосовуючи непараметричні статистики

Ключові слова: система управління якістю, показник якості, критерій оцінювання, непараметричні статистики, графічна модель

Разработана методика количественного оценивания процессов системы управления качеством предприятий, которая включает процедуру получения их оценок на безразмерной шкале. В качестве зависимостей предлагается использовать порядковые статистики, которые учитывают максимально-допустимое, минимально-допустимое и его наилучшее (оптимальное) значение. Предлагается оценивать системы менеджмента качества на этапе функционирования через оценки взаимосвязанных процессов, применяя непараметрические статистики

Ключевые слова: система менеджмента качества, показатель качества, критерий оценки, непараметрические статистики, графическая модель

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DEVELOPMENT OF QUALIMETRIC APPROACHES TO THE PROCESSES OF QUALITY MANAGEMENT SYSTEM AT ENTERPRISES ACCORDING TO INTERNATIONAL STANDARDS OF THE ISO 9000 SERIES

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1. Introduction

Efficient provision of product quality largely depends on enterprise management system. Achieving the goal of improving product quality assurance system is possible by way of implementation and certification of the quality management system (QMS) of an enterprise in accordance with the requirements of international standards of the ISO 9000 series, which has long and successfully been used by enterprises in the world.

Thus, for example, in 2012 the total quantity of certified organizations in the world was around 700 000, in 2013 – more than 870 000. During 2013, the number of countries in the economies of which the international standards ISO 9001:2008 are used increased from 154 to 162. The number of certificates of ISO 9001:2008 issued in 2013 in China alone amounted to over 140 000. And also in China more than 9 000 certificates for the international ecological standards ISO 14000 were issued. There are about 3 000 registered certificates of ISO 9001:2008 in Ukraine, which ranks 42 in the world by this indicator.

In accordance with the international standards of the ISO 9000 series, efficient management becomes a key prerequisite for successful functioning of any organization. Hence the need for objective diagnosis of existing systems of management, for analysis of the state, for identifying the directions of their flexible and dynamic adaptation to changing conditions of organizations' performance. As confirmed by the practice, development and implementation of such an organizational structure that meets international quality standards significantly reduces production with defects (by 50–60 %), while reducing costs (by around 40 %) of such technological operations as controlling and testing of finished products. The expenditures for quality under these conditions decrease twofold while profitability of an enterprise or a business activity increases by 15–20 %.

Despite an intensive work for the certification of quality management systems, the majority of Ukrainian enterprises were not able to achieve the improvement in economic indicators, which is linked to the lack of efficient methods of quantitative assessment of the quality of the processes of QMS and the system in general. After all, as was written by a famous specialist in quality management field Professor Deming, “One can manage only what one can evaluate”. So there appears an actual task of developing criteria for the functioning of QMS, as well as creating methods of their parametric analysis and comprehensive evaluation, brought to practical implementation. To do this, it is necessary to create a set of models, methods, algorithms and methods of monitoring, parametric analysis and comprehensive evaluation of quality system, which make it possible to increase efficiency of the functioning of enterprises. Such a set of models should cover all the elements of this system and main processes that ensure the quality of enterprise management.

Therefore, development of a methodology of quantitative assessment of the processes of quality management system of enterprises in accordance with modern requirements of international standards of the ISO 9000 series is an actual scientific-applied task.

2. Literature review and problem statement

Analysis of the concept of “quality management system” as the object of qualimetry revealed that the problems of assessment and analysis of QMS are dealt with in a number of works of the Ukrainian and foreign scientists. The author of scientific paper [1] demonstrated the need for a quantitative assessment of quality of the processes that are included in a quality management system, but he did not offer a mathematical apparatus for objective evaluation because expert assessments are used. The paper [2] proposes general principles of operational evaluation of the quality of products and processes, but the method of using experts is also applied, which has elements of subjectivity. The work [3] is associated with distribution functions of limit statistics that can be used to change various dimensional quality indicators to a dimensionless scale, but such methods are absent. The paper [4] proposes to apply desirability function for the assessment of product quality on a dimensionless scale, which refers to the distribution function of the smallest member in the sample [3], but the method of constructing an assessment scale is absent. The work [5] is devoted to the study of models of distribution of the results of expert evaluations of quality by applying a method of benefits that allows receiving the assessment of a product, service or process quality, engaging a minimal number of experts, but expert assessments are not uniform in the tools of evaluation and, as a rule, we have to deal with various dimensional quality indicators.

The analysis of scientific literature on qualimetry revealed [6–13] that it is not acceptable for QMS assessment to apply existing methods of evaluation due to various reasons:

1. There are no similar systems at various enterprises [6] because their complexity depends on the type of manufactured products or services, the scope and structure of enterprises, the processes that are performed at an enterprise [7], on personnel qualification and many other factors.

2. There is no a single methodology for evaluation [8, 9] as every enterprise must independently determine the objectives of quality and quality system indicators, depending on the stage of its development and perfection.

3. A large variety of qualimetric methods of assessment [10, 11] requires thorough scientific research concerning optimality and the efficiency of their use for each particular case.

The proposed approaches to the development of quality management systems are constantly evolving [12], the tools and management methods are developing, information technologies are progressing, as well as communication systems, new management concepts emerge and rapidly spread [13], however there appears the necessity of solving a scientific and practical task of developing a methodology for assessing QMS as the object of qualimetry.

As processes are different in their nature, their quality indicators have different measurement units and different optimal values, indicators of quality of processes can be divided into 4 groups [14]:

1. Group of quality indicators in which the optimal (best) value tends to the lower limit of the tolerance field. For example, the number of defective products, the number of accidents, the number of fatal cases, late-comings, delays, etc. In this case, the lower the value of the indicator, the better.

2. Group of quality indicators in which the optimal (best) value tends to the upper limit of the tolerance field. For example, reliability, effectiveness, efficiency, success, etc. In this case, the higher the value of these indicators, the better.

3. Group of quality indicators in which the optimal (best) value tends to the middle of the tolerance field. For example, accuracy of dimensions in the manufacture of the parts, accuracy in maintaining the temperature in a technological process, accuracy during execution of some work, etc. As a rule, these indicators tend to the middle of the tolerance field.

4. Group of quality indicators in which the optimal (best) value tends to the edges of the tolerance field. For example, the largest productivity at the lowest costs.

Given that different groups of indicators have different optimal values, the individual dependencies were built for each group. The function of dependencies is known in the literature as the Harrington function, which was used for the evaluation of quality of technical objects [15]. The function is exponential and is the first limit distribution of extreme values in the sample of random variables and it has a number of features that attracted researchers to practice its application.

First, the first limit distribution of extreme values can be linearly converted into an expression that does not contain any parameters, so there is no need for the assessment of parameters as it is a rather complicated mathematical problem.

Second, due to the principle of symmetry present in the function, with a distribution function of the lowest value in the sample of random variables, one can get a distribution function of the highest values of random variables. That is, to receive an interval limited by the specified functions, in which an indicator of quality is present.

Third, by using the principle of symmetry, one can get a series of intermediate functions that will allow optimizing requirements to the quality of the process.

Fourth, all functions allow transferring the values of quality indicators in a dimensionless scale.

Fifth, all functions have exponential form and never cross the value of one on the horizontal axis. This corresponds to the ideology of quality, since quality must strive for the value of one.

Sixth, all functions cross the value of zero on the horizontal axis. This corresponds to the ideology of quality, since quality may equal zero.

Having conducted the analysis of scientific research [15, 16], it should be noted that the proposed dependencies are nothing more than a convenient deal, which makes it possible to solve practical problems in qualimetry. Ease of use of the considered dependencies is in the fact of their lacking parameters, which, in turn, should not be evaluated. In this case, the considered methods are not devoid of drawbacks that need addressing.

A series of dependencies takes into account four groups of indicators of quality, but only one type of dependency is applied – double exponential distribution. The authors [16] accept that the type of dependency is not associated with the heterogeneity of the process, but, due to the principle of symmetry, raise, lower or return it.

Thus, indeed, one can consider such a system of dependencies universal and convenient to use, but it leads to rough estimations that are not always objective.

As a result of the analysis of existing studies [1–16], one can conclude that for the development of methodology of quantitative assessment of the processes of quality management system of enterprises, it is necessary to look for dependencies, which would take into account the above mentioned drawbacks.

3. The purpose and objectives of the study

The aim of the work is to develop qualimetric approaches for the assessment of the processes of QMS at enterprises.

To achieve the set goal, the following tasks of research were formulated:

– to develop a system of dependencies between individual various dimensional parameters of quality of processes with a dimensionless scale of estimation using desirability functions that have the parameter of form;

– to propose criteria and methods of evaluation of the systems in the process of their operation given limited information on the indicators and on the quality and the lack of knowledge of the law of their distribution as random variables.

4. Desirability functions for assessment of quality of processes

It is proposed to use serial statistics as dependencies, which would exclude the shortcomings described in the previous section. These dependencies must take into account maximally acceptable value of the indicator of quality of the process and its maximally acceptable value as well as its best (optimal) value. In addition, it is proposed to find a single (universal) form of dependency and to change its steepness by the parameter of form, which will allow using them to assess different processes with different requirements to quality. Similar dependencies [16] were applied for the evaluation of quality of products.

Since QMS processes have different nature, complexity degree and level of significance in the system, then their quality indicators are dissimilar and they have different assessment scales. For the assessment of QMS, it is necessary to bring the values of quality of all processes to a single, preferably dimensionless scale. We propose the following function as a desirability function for the transfer of various dimensional parameters of quality of processes of a system into a dimensionless scale:

$$F_x = \begin{cases} 0, & X_i \le X_{imin}, \\ \left[\dfrac{X_i - X_{imin}}{X_{imax} - X_{imin}} \right]^k, & X_{imin} < X_i < X_{imax}, \\ 1, & X_i \ge X_{imax}, \end{cases} \qquad (1)$$

where X_i is the real (measured) value of the indicator of quality of the process; X_{imin} is the minimal value of the indicator of quality of the process; X_{imax} is the maximal value of the indicator of quality of the process; R is the scattering field of indicators of quality of the process.

$$k = \left(\frac{R}{X_{max} - X_{min}} \right)$$

is the parameter of form, which is the ratio of the scattering field to the tolerance field of the indicator of quality of the process. A tolerance field is the difference between maximally and minimally permissible values.

The proposed function (1) takes into account permissible maximal and minimal values of the parameter of quality of the process and proposes the best (optimal) indicator. The parameter of form and steepness of the function allows assessing the processes different in significance that have different requirements to quality. With the change in the parameter of form (from 0.1 to 1 with a step 0.1), the view of the function (a series of functions) changes (Fig. 1). The mentioned figure displays, as an example of indicator of quality of the process, accuracy of dimensions among the elements of a complex assembled structure, as it is the only indicator of quality of the process of assembling. In this case, the best result is the dimension of 100 mm. Reducing it to 70 mm leads to defect, that is, quality of the process of assembling equals zero.

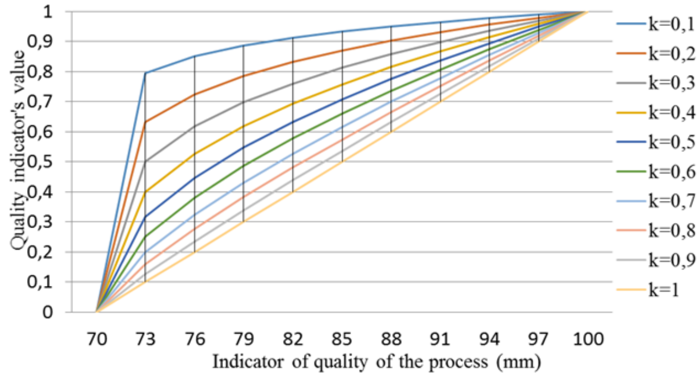

Fig. 1. View of desirability function (1), at the parameter of form k from 0.1 to 1

Let us accept the parameter of form

$$k = \left(\frac{X_{max} - X_{min}}{R} \right),$$

that varies from one to ten with a step 1, then the desirability functions will be concave down, as shown in Fig. 2.

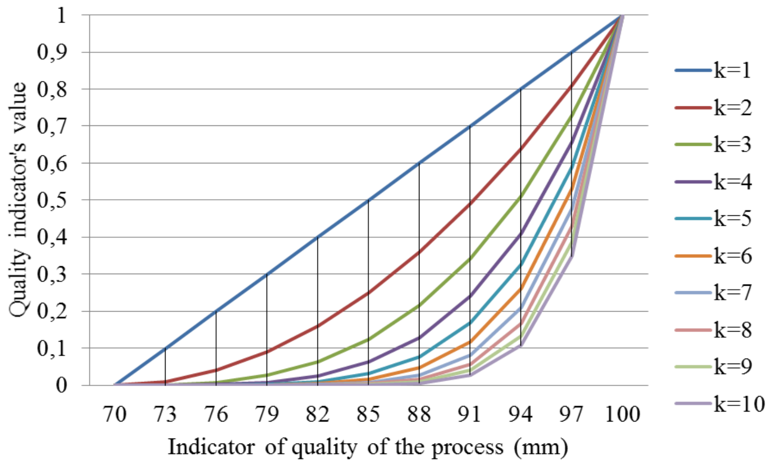

Fig. 2. View of desirability function (1) at the parameter of form k 1–10

If the optimal (best) indicator of quality is the middle of the tolerance field and in this case the parameter of form varies from 0.1 to 1 with a step 0.1 or from 1 to 10 with a step 1, the desirability functions will have the view:

$$F_x = \begin{cases} \left[\dfrac{X_i - X_{imin}}{t_i - X_{imin}} \right]^k, & X_{imin} \le X_i \le t_i, \\ \left[\dfrac{X_i - X_{imax}}{t_i - X_{imax}} \right]^k, & t_i < X_i \le X_{imax}, \\ 0, & X_{imin} > X_i > X_{imax}, \end{cases} \qquad (2)$$

where t_i is the middle of the tolerance field; R is the scattering field of the indicators of quality.

In this case, the system of desirability functions will have the view shown in Fig. 3.

The mentioned figure displays, as an example of indicator of quality of the process, the accuracy of diametric dimension of the part "shaft", which is processed on a lathe. As is known, during the manufacture of parts on set lathes, the best indicator of quality tends to the middle of tolerance field.

Using this type of desirability function will make it possible to receive a quality indicator of the processes on a dimensionless scale, while the parameter of form will allow selecting the required function, depending on the accuracy and significance of the process.

5. Methodology of QMS assessment at the stage of operation

It is proposed to assess QMS at the stage of operation through the evaluation of a set of interrelated processes, i.e. to combine the assessments of different processes in one set of data and evaluate it as a whole. This procedure will increase the amount of information on the assessment of quality of the system as the totality of processes that will allow assessing the whole system with more objectivity and reliability.

For the solution of this task, it is proposed to apply statistical methods using nonparametric statistics. Nonparametric statistics do not require knowledge of the law of distribution of a random value, but require a larger amount of statistical data that can be provided by combining ratings of quality processes.

It is proposed to receive indicators of quality of the processes by a dimensionless scale, but since the processes should be periodically evaluated, then we will obtain a time series (the implementation) of quality indicators. As the number of the processes equals n, and they all have a uniform assessment scale, then one can build them in one coordinate system and receive m of quality assessments that together characterize the quality of the system (Fig. 4).

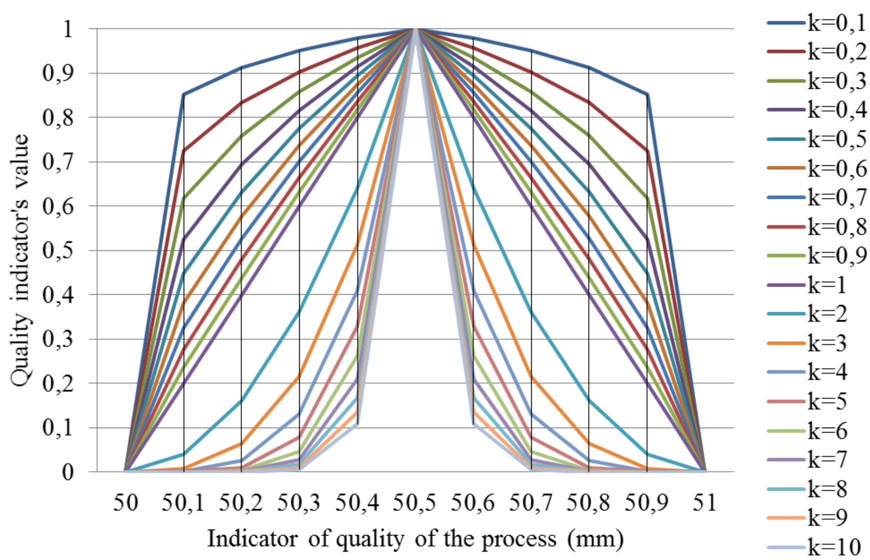

Fig. 3. Desirability functions of model (2), at the parameter of form 0,1–10

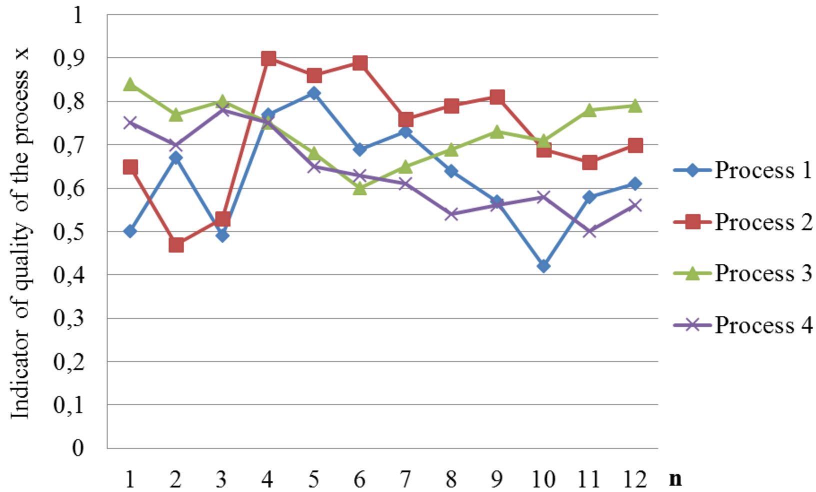

Fig. 4. Set of assessments of the quality of QMS processes

Let us prepare a set of assessments for mathematical processing. For this, we propose to check all the values for gross errors, applying a nonparametric criterion of Fisher:

$$\left|x_n - \bar{x}_{n-1}\right| \geq S_{n-1} t_\alpha \sqrt{\frac{n+1}{n(n-1)}}, \qquad (3)$$

where

$$\bar{x}_{n-1} = \frac{\sum_{i=1}^{n-1} x_i}{n-1}, \quad S_{n-1} = \sqrt{\sum_{i=1}^{n-1}\left(x_i - \bar{x}_{n-1}\right)^2}.$$

If the inequality is valid (3), then the value x_n may not be considered random and used in this set. In other case, the value x_n may be considered random and further analysis of the set may be run with regard to this value.

It should be noted that the set of data that consists of mn estimates is sufficient to provide necessary capacity of the Fisher criterion for the estimation of gross errors.

It is necessary to assess the set for stationarity, since the type of stationarity or non-stationarity of a process depends on the choice of mathematical apparatus for further research. For the evaluation of the stationarity of a process we will apply criteria of nonparametric statistics – the criterion of series and the criterion of inversions. To do this, one must obtain a time series of multiple processes in the same coordinate system as shown in Fig. 4, find average values

$$\bar{X}_i = \frac{1}{n}\sum_{i=1}^{m} X_i,$$

find the number of series r and compare it to the limit, minimal and maximal values of the number of series at this level of significance. Or, in other words, it is necessary to maintain the validity of the inequality

$$g(1-\alpha; N_1, N_2) < r < G(\alpha; N_1, N_2), \qquad (4)$$

where r is the number of series; α is the level of significance; g and G are the lower and upper limits for the number of series, respectively.

If the number of series is outside this interval, then the process of changing the parameters of quality of the system can be considered stationary at the level of significance α, in other case – not. Similarly, using the existing method, one can assess any process for stationarity by the criterion of inversions.

To be able to combine the implementations of various processes in one set, one must ensure that these implementations are homogeneous. If they turn to be homogeneous, then one can use statistical data of the implementations of all processes in the aggregate, which will increase the amount of statistical information. For the assessment of homogeneity of many implementations of different processes, we propose to apply a nonparametric criterion – a van der Waerden test.

For this purpose, it is necessary to create ordered (growing) variation line from the elements of all implementations and to determine the sums:

$$y_{i=1}^{m} = \sum_{y_i} \varphi\left(\frac{S_{im}}{n_m + 1}\right), \qquad (5)$$

where n_m is the number of observations of each implementation of m processes; s_{im} is the serial number of the i-th element in the appropriate variation line m; φ (z) is the function that, in the interval 0<z<1, accepts only final values and satisfies the condition $\varphi(1-z) = -\varphi(z)$. In this case, the following condition must be fulfilled: $n_1 = n_2 = n_m$.

As an example, we tested the hypothesis of homogeneity of the implementations of four processes, obtained as a result of the auditing procedure of "PROMSTANDART" LLC (Kyiv, Ukraine). From the received results of the audit of the quality processes at "PROMSTANDART" LLC we obtained general variation line of quality indicators in ascending order (Table 1), in which we assigned sequence numbers to each value.

Table 1

Variation line of implementations of four processes

Pr. 1	0,12	–	–	–	–	0,24	–	0,26	–		–	–	–	–	–	0,45
Pr. 2	–	0,16	–	–	0,21	–	0,25	–	–	–	–	–	–	0,41	–	–
Pr. 3	–	–	0,18	–	–	–	–	–	–	–	0,28	0,29	–	–	0,43	–
Pr. 4	–	–	–	0,2	–	–	–	–	0,27	–	–	0,33	0,4	–	–	–
#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

To simplify the calculations, we determined the values

$$\varphi\left(\frac{i}{n}\right).$$

By the formula (5) we defined the value for each process:

$$y_1 = \varphi\left(\frac{1}{17}\right) + \varphi\left(\frac{6}{17}\right) + \varphi\left(\frac{8}{17}\right) + \varphi\left(\frac{16}{17}\right);$$

$$y_2 = \varphi\left(\frac{2}{17}\right) + \varphi\left(\frac{5}{17}\right) + \varphi\left(\frac{7}{17}\right) + \varphi\left(\frac{14}{17}\right);$$

$$y_3 = \varphi\left(\frac{3}{17}\right) + \varphi\left(\frac{11}{17}\right) + \varphi\left(\frac{12}{17}\right) + \varphi\left(\frac{15}{17}\right);$$

$$y_4 = \varphi\left(\frac{4}{17}\right) + \varphi\left(\frac{9}{17}\right) + \varphi\left(\frac{12}{17}\right) + \varphi\left(\frac{13}{17}\right).$$

We identified the values of limits of critical area for the van der Waerden test at a=0.05. If the specified sum of elements (5) is within the limits of a critical area, then the values of all implementations of the processes are homogeneous and they may be analyzed together.

In order to resolve capacities of managing the processes of QMS and the system as an interrelation of processes, it is necessary to determine that its statistical characteristics vary randomly or have a systematic component. To test the randomness of quality processes indicators, it is proposed to apply the nonparametric criterion of Abbe-Linnik.

As a statistical characteristic for checking the randomness of the process at this criterion, the ratio is used

$$r = \frac{g^2}{s^2}, \tag{6}$$

where

$$g^2 = \frac{1}{2(n-1)} \sum_{i=1}^{n-1} \left(x_{i+1} - x_i\right)^2.$$

If the process has a systematic component, then the value s^2 will be much larger than g^2.

With a valid inequality $\{r \le r_\alpha\}$, the process has a systematic component; in other case it is absent.

Therefore, by applying the criteria of nonparametric statistics and the proposed method, one can receive the assessment of QMS over the period of its operation.

6. Discussion of the results of study of quantitative assessment of the processes of quality management system at an enterprise, based on nonparametric statistics

Conducted research into analysis of the methods of quantitative assessment of the processes of quality management systems according to international standards of the ISO 9000 series made it possible to offer a system of dependence of quality indicators (Fig. 1–3), each of which has maximally-permissible, minimally permissible and optimal values of indicators.

The proposed system of dependencies has a major advantage over the existing ones [1–5], which manifests in the fact that by changing the parameter of form, one may receive different assessments of the indicators of quality on a dimensionless scale, which varies from zero to one (in a step 0.1).

This methodology can be easily applied when evaluating quality of products, processes, services, systems and other objects of qualimetry because of its simplicity and versatility, because mathematical dependencies are simple in their application since they do not require complicated mathematical calculations, confirmed by empirical research at "PROMSTTANDART" LLC (Table 5, Fig. 4).

An algorithm of assessment of QMS at an enterprise is presented, which is generalized for the evaluation of processes in any organization that aims to conduct the audit with quantitative assessment of the efficiency of functioning of a system. In this case, the number of processes and their quality indicators vary, which is taken into account in the formulas (1)–(5).

The disadvantage of this approach is that the so-called coefficient of accuracy is accepted as the parameter of form k, i.e. the ratio of the magnitude of random variables to the tolerance field.

The next step of scientific research into this area may be receiving such a mathematical dependence that would, in addition to the parameter of form, have a larger scale, which could allow applying this method more universally.

7. Conclusions

1. A method of quantitative assessment of QMS at enterprises was developed, which included the designed system of dependencies between individual various dimensional parameters of quality of the processes with a dimensionless scale of assessment by using desirability function that have the parameter of form. By using such functions, one may obtain a quality indicator of any process on a dimensionless scale.

2. A method of assessment of QMS at the stage of operation was proposed, using the criteria of nonparametric statistics that can be applied under conditions of limited information about quality indicators and the lack of knowledge of the law of their distribution as a random value. As QMS refers to socio-economic systems, it is difficult to be assessed by using statistical methods.

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