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THEORETICAL ASPECTS OF THE TECHNICAL LEVEL ESTIMATION OF ELECTRICAL ENGINEERING COMPLEXES

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The results of the analysis of methods allowing to evaluate the technical level of the electro technical complex (ETC) are presented and an original technique based on the application of the integral indicator is presented. The characteristic of each stage of the technique is given. The proposed scientific and methodological apparatus for assessing the technical level of the ETC is illustrated by the examples of the executive elements of the ETC comparison (internal combustion engines) using an integral quality index that links both the main characteristics of the samples and the means spent for achieving them. The proposed approach for assessing the technical level and quality of the ETC on the basis of an integral indicator should be carried out already at early stages of the life cycle when solving the following problems: the rationale for the economic feasibility of developing new or improving the quality of the produced ETCs; choice of the best option for the developed ETC; justification of requirements for the ETC; decision-making on the establishment and removal of ETC from production; substantiation of the rules of operation of the ETC in various conditions.

***Key words*:** technical level, quality, methodology, electrotechnical complex, internal combustion engine

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Introduction. The task associated with the improvement of the national scientific and technical and operational capacity through the development of technology and world-class technology is highly relevant [15-17, 19, 20]. One of the main approaches to solving this problem is the use of advanced technologies, extensive scientific research, the introduction of modern achievements of science and technology, as well as the constant growth of the requirements for the quality of created complex technical systems.

An analysis of a number of sources [8-11] shows that the assessment of the quality of products (products, models, systems) is carried out at the development stage (technical level is assessed), at the stage of acceptance a prototype and deciding of the launch of production (the technical level is estimated) and at the stage of production, in the latter case, the technical level and the quality of production are assessed.

An important properties for assessing the quality of electrical facilities (ETC) are [11-14]: a technical level that reflects materialization in the production of scientific and technological achievements; operational level associated with the technical side of the use of products (care of the product, repair, etc.); technical quality, assuming the relationship of expected and actual consumer properties in the operation of the product (functional accuracy, reliability, service life); aesthetic level, which is characterized by a complex of aesthetic feelings and views.

The evaluation of the technical level of complicated electrotechnical complexes (CETC) involves a set of actions, including, firstly, the choice of the nomenclature of indicators that characterize the technical perfection of the evaluated products, secondly, the determination of the values of these indicators, and, thirdly, the comparison of them with the base ones [9, 11, 12].

Various methods are known for comparing the variants of ETC samples and evaluating their quality [3, 4, 6, 12, 18, 20]. For example, in [5], a technique for creating technical level maps and quality of propulsion power plants on the basis of the criteria obtained by the authors is proposed: a dimensionless complex characterizing the degree of forcing, mass, reliability and longevity of the engine; Expressions for calculating the availability factor (engine technology); criterial equation of technical level of marine engines. In [2] criteria for the evaluation of the quality of thermal engines are proposed.

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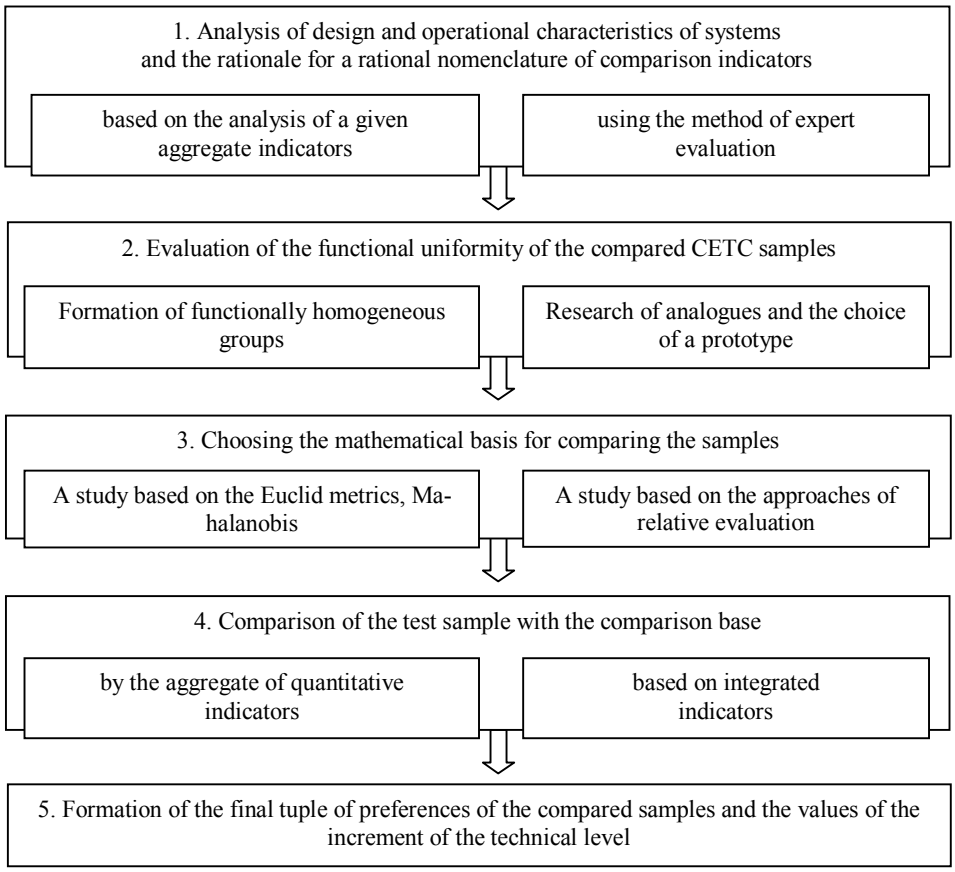


Fig.1. Structural-logical scheme of the methodology for assessing the ETC technical level

Methodology and methods of research. Analysis of the provisions of the efficiency theory of ETC and normative and technical documentation on product quality management made it possible to develop a general methodology for assessing the technical level of the ETC, consisting of the following stages (Fig.1):

1) selection of the nomenclature of quality indicators and justification of its necessity and sufficiency;

2) the choice or development of methods for determining the values of quality indicators;

3) choice of basic values of indicators and initial data for determining the actual values of the quality indicators of the estimated ETC;

4) determination of the actual values of the quality indicators of the evaluated CATC options;

5) comparative analysis of options for possible solutions and finding the best.

The most important step in assessing the quality of any technical system, for example, internal combustion engine (ICE), in its creation, testing, certification and operation is the selection and justification of the nomenclature of comparison indicators. In accordance with the definition of GOST [8, 9], a quantitative characteristic of one or several properties of products (samples, products) that make up the quality considered in relation to certain conditions for the creation and operation of products is called a quality indicator. Quality indicators are determined taking into account the characteristics of each type of product [1, 11, 12]. For example, a characteristic of the quality of an internal combustion engine is often taken as a vector of indicators of potential performance of the internal combustion engine, usually power, engine mass, engine speed, cylinder diameter, average effective pressure, average piston speed, etc. [2, 6].

The plotting of a vector exponent is much more complicated than a scalar one. Therefore, in practice, the most common is the approach, in which from several particular indicators it is going to a single function of correspondence, i.e. to a single objective function of the exponents [6, 12]. All these methods use additional information about the relative importance of individual indicators.

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Let us consider a brief description of each stage of the proposed methodology.

It is known that the nomenclature of quality indicators is very numerous and is set taking into account: the purpose and conditions of products use; requirements of customers; tasks of product quality management at all stages of the life cycle; composition and structure of the characteristic properties of products. In general, there are 10 groups of unit indicators [1, 9, 10]: 1) designation; 2) reliability and durability; 3) economy; 4) ergonomics; 5) manufacturability; 6) unification; 7) ecological compatibility; 8) security; 9) aesthetic; 10) patent and legal.

Note that there are several methods used to compare the variants of images of a complex system with the purpose of assessing their technical level and quality [9, 12]. These methods allow you to rank the compared options according to the conditional preference criteria depending on the selected qualitative indicators. The results of such studies are usually written in the form of a matrix, the elements of which are the ranks (sequence number) of the corresponding sample. The row number of each element of this matrix corresponds to the number of the indicator in question, and the column number to the number of the sample in question. The number of rows is equal to the number of qualitative indicators considered, and the number of columns is equal to the number of samples considered. Coefficients of rank correlation serve as an integral measure of preference for one option over another [11, 12].

Rational nomenclature of comparison indicators, in common, is based either on the basis of an analysis of a given set of indicators, or using methods of expert evaluation.

When evaluating the functional homogeneity of the ETC types being compared, as well as the choice of analogs and the comparison base, it is proposed to use methods based on dynamic condensations (for the cases of one-dimensional comparison) and multivariate hierarchical classification.

The algorithm for applying the comparison method on the basis of quantitative indicators includes the following main stages:

1) definition of the list of compared variants and the standard;

2) determination of the nomenclature of single indicators characterizing the perspective version of the ETC;

3) normalization of single indicators (reduction to a dimensionless scale in the interval from zero to unity, calculation of the exponents q_i);

4) determination of the significance («weight») of each unit indicator (α_i);

5) calculation of proximity coefficients (ρ_j) of the compared variants to the standard: the smaller the value of ρ_j, the closer the compared version to the standard ($\rho_j \in [0\ldots1]$).

6) Based on the calculated values of proximity factors, a tuple of pre-reading of the considered variants is formed.

The proximity coefficient

$$\rho_j = \left[\sum_{i=1}^{n} \alpha_i \left(1 - \tilde{q}_{ij}\right)^2\right]^{1/2},$$

where q_{ij} is the value of the index of the i-th version of the sample, compared with the j-th index; n is the number of alternative variants of ETC.

Example 1. Suppose that the ETC is a set of technical devices, among which we can distinguish executive devices – internal combustion engines. We will consider the application of the cluster analysis method to create a group of objects close to the characteristics that are estimated by comparing the four types of medium-turn ICE. Numerical values of their characteristics are taken from the catalog of products manufactured by JSC «RUMO», OJSC «Kolomensky Zavod» and works [6]. Table 1 gives the initial data for comparing the following engines: 6FH22/28 (E_1), 6PH36/45 (E_2), 8CH26/26 (E_3) and 6CH20/30 (E_4).

Comparison of the diesel engines will be carried out according to the characteristics of $X_1 - X_{11}$: X_1 – the ratio of the stroke of the piston to the diameter of the bush of the cylinder; X_2 is the average effective pressure; X_3 – average speed of the piston; X_4 – engine boost; X_5 – cylinder power; X_6 – piston power; X_7 is the standard specific gravity; X_8 is a liter weight; X_9 – overall power; X_{10} – specific material consumption; X_{11} is the specific energy saturation, and the potential of the characteristics ω_j.

Table 1

Baseline data for the study

Factor	Technical characteristics of power plants										
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
Object											
E_1	1.27	1.76	9.33	16.47	156.67	0.412	13.83	20.37	124.24	0.17	5785
E_2	1.25	1	7.5	7.53	191.67	0.188	25.13	10.52	55.18	0.42	2388
E_3	1	1.36	8.67	11.76	156.25	0.294	8.4	9.51	148.67	0.11	8929
E_4	1.5	2.42	10	24.17	190	0.605	9.39	18.93	113.87	0.12	8523
Quantitative characteristics											
$\widetilde{m}_{X_j}$	1.255	1.635	8.875	14.983	173.648	0.375	14.188	14.833	110.49	0.205	6406.25
$\widetilde{G}_{X_j}$	0.204	0.609	1.065	7.131	19.859	0.179	7.668	5.609	39.654	0.146	3020.882
ω_j	0.000066	0.000196	0.000343	0.002298	0.006399	0.000058	0.002471	0.001808	0.012779	0.000047	0.973534

The application of cluster analysis in its general form reduces to the following stages: selection of the selection of objects for clustering; the definition of a set of variables by which objects in the sample will be evaluated; normalization of the values of variables (if necessary); calculating the value of the measure of similarity between objects; application of the cluster analysis method to create a group of similar objects (clusters); presentation of analysis results.

Calculating the mathematical expectation ($\widetilde{m}_{X_j}$) and the standard deviation ($\widetilde{G}_{X_j}$) of each of the characteristics of the object using the formulas given in [11-13], we obtain a normalized matrix (Table 2), whose elements are calculated by the formula

$$z_{ij} = \frac{x_{ij} - \widetilde{m}_{X_j}}{\widetilde{G}_{X_j}},$$

where $j = 1 \div 11$; $i = 1 \div 4$.

Table 2

The normalized matrix for the comparison of samples

Object	The normalized values of the characteristics										
	z_1	z_2	z_3	z_4	z_5	z_6	z_7	z_8	z_9	z_{10}	z_{11}
E_1	0.073	0.2054	0.4270	0.2086	–0.8549	0.2085	–0.0466	0.9873	0.3467	–0.2402	–0.2057
E_2	–0.0245	–1.0436	–1.2906	–1.0451	0.9075	–1.0451	1.4271	–0.7689	–1.3948	1.4755	–1.3302
E_3	–1.2477	–0.4519	–0.1924	–0.4519	–0.8761	–0.4519	–0.7548	–0.9489	0.9628	–0.6519	0.8351
E_4	1.1988	1.2901	1.0559	1.2884	0.8234	1.2885	–0.6259	0.7305	0.0852	–0.5833	0.7007

Since each variant of the projected sample of the ETC is characterized by a set of technical characteristics, the evaluation (comparison) of the variants is carried out in their totality. In this case, the calculation of the weight coefficients (potentials) of the characteristics of objects is carried out on the assumption that a «weighted» Euclidean distance is used as a measure of proximity. Potentials of characteristics can be determined using expression

$$\omega_j = \frac{\widetilde{G}_{X_j}}{\sum_{j=1}^{m} \widetilde{G}_{X_j}},$$

where m – the number of qualitative indicators considered.

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It is known [11, 12] that for the degree of closeness (measure of deviation) of objects in this case, a Euclidean metric can be adopted. The calculation of the «weighted» Euclidean distance is carried out by the formula

$$d_{ik}^2 = \sum_{j=1}^{m} (x_i^{(j)} - x_k^{(j)})^2 \omega_j,$$

where d_{ik} is the distance (total) between objects i and k; $x_i^{(j)}$ – j-th characteristic of the i-th object; $x_k^{(j)}$ – j-th characteristic of the k-th object.

As a result, we obtained a matrix consisting of four columns and four rows (Table 3). At each iteration (in presented example, three iterations), the minimum distance between the elements in the resulting matrix d_{pq} (where p and q are the numbers of the closest clusters) is first determined. After their determination, these clusters are combined, the elements of a new cluster, for example p*, are calculated by the expression

$$d_{rp*}^2 = d_p d_{pp*}^2 + d_q d_{qp*}^2,$$

where d_p, d_q – are the weighted average proximity measures, $d_p = m_p/(mp + mq)$, $d_q = m_q/(m_p + m_q)$, m_p is the number of elements in cluster p; m_q is the number of elements in the cluster q.

Table 3

Step-by-step selection of clusters

Cluster	1st iteration			
	1	2	3	4
1	0	1,3057881	1,0687414	0,82279457
2	1,3057881	0	4,66911446	4,0738512
3	1,0687414	4,66911446	0	0,05971028
4	0,82279457	4,0738512	0,05971028	0
D_{min} = 0,05971028	d_p = 1/2		d_q = 1/2	
Cluster	2nd iteration			
	1	2	3*	
1	0	1,3057881	0,94576798	
2	1,3057881	0	4,37148283	
3*	1,0687414	4,66911446	0	
D_{min} = 0,94576798	d_p = 2/3		d_q = 1/3	
Cluster	3d iteration			
	1*	2		
1*	0	1,3057881		
2	3,34958459	0		

Graphical representation of the results of multidimensional comparison of options is advisable to perform as a hierarchy graph (Fig.2). It is constructed as follows: on the basis of the similarity matrix, two closest objects are identified, i.e. having a maximum similarity coefficient, then the similarities between all the remaining objects and this new object are recounted in the matrix and so on.

As a result of the calculations, the final tuple of preference for compared samples of complex technical systems (engines) was obtained: $E_1 > E_3 \sim E_4 > E_2$.

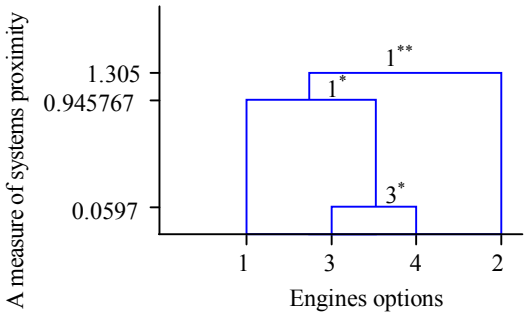


Fig.2. The hierarchy (dendrogram)

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Thus, the carried studies have shown that the engines E_3 and E_4 are close to each other by the characteristics under consideration and are the closest to E_1.

Example 2. Let us consider an example of an integral quality index linking both the main characteristics of the samples and the means spent for achieving them. It is known that when choosing methods for comparing ETC, single, complex and integral indicators of quality are used [7, 13, 14, 16].

The complex indicator of product quality is calculated as the sum of the products of the indicators of the evaluated properties by the coefficient of weight of this indicator [7, 11]. As a rule, the weight of the indicator is established by expert methods [2, 3, 5-7].

The multiplicative form of the complex quality indicator of the system (object) on the basis of the geometric mean weighted is represented by the expression

$$\overline{Q}_{q_j} = \sqrt[n]{\prod_{i=1}^{n} Q_{q_j}^{\alpha_i}},$$

where $\overline{Q}_{qj}$ – the normalized values of quality indicators.

Comparison of the prospective ETC with the existing ones is usually performed by comparing its indicators with the indicators established by state standards. Therefore, when assessing the level of quality, for example, ICE, determine the ratio of a single indicator of a property to the base value or vice versa, depending on the effect of the indicator under study on the quality.

If it is necessary to give an estimation by the totality of the indicators, then use the generalized indicator [2, 3, 5-7, 11, 12], which can be represented as: the main relative unit quality index, integral or complex quality index [2, 6, 7, 11, 12].

In work [7] it is offered to estimate a level of quality of a diesel engine at each stage of functioning as function of five arguments: 1) ecological efficiency of a design; 2) economy of construction; 3) design features of engines; 4) technological production of manufacturing, operation, maintenance and repair; 5) production labor for manufacturing, installation, maintenance and repair.

The analysis showed that when evaluating the samples of ETC elements, for example, ICE, it is reasonable to use the integral quality index, which is one of the most important indicators of the final production efficiency and represents the ratio of the beneficial effect in natural units from the application (consumption) of production to the total cost of its creation and operation.

In general, the integral quality indicator of the ETC can be written as a function [12, 13], depending on the following characteristics: QI_{bk} – k-th measured quality index of the baseline ETC; QI_{bj} – j-th non-measurable quality index of the basic ETC; TC – the total capital (one-time) costs for the creation of the ETC, conditional units of value (conventional units of the item); TCC – total operating (current) costs for the entire service life, cond. units st.; E_n – the norm of bringing different costs; α_k and β_j are the weight coefficients of the corresponding unit quality indicators, calculated by the expert method; t – service life (warranty service life) of products, years.

Total capital (one-time) costs are calculated by the formula

$$TC = TCC(1 - E_n)^{-h},$$

where TC – total capital expenses for creation of production at the moment of their investment (without reduction to the settlement year); h – the time from the moment of investment of capital expenditures to the accounting year.

The total operating (current) costs for the whole lifetime are calculated according to the formula

$$TC = \sum_{i=1}^{t} OC(1 + E_n)^{i-1-l},$$

where OC – operating costs, carried out in the i-th year, cond. units st.; l – time from the beginning of operation to the estimated year, years.

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The value of the E_n standard is established by the competent authorities. In the absence of an approved standard for bringing the cost of differentiation (up to 10 years) to the most widespread range for the evaluation of product quality, it is recommended to take $E_n = 0{,}04 \div 0{,}015$ [11-13].

A detailed description of the calculation of the components of the integral quality index is given in [12]. In this form, the integral indicator allows us to more flexibly evaluate the quality of existing and projected products, as well as to compare alternative systems options by quantitative and qualitative indicators [10, 12].

Thus, the integral quality index of the ETC

$$I = F(QI_{bk},\ IQ_{bj},\ TC,\ OC,\ t,\ E_n,\ \alpha_k,\ \beta_j),$$

Example 3. In order to test the efficiency of the methodology, let us consider the technical level estimate of the advanced ICE on the basis of a comparison with the existing ones in terms of the indices presented in Table 4. The data for the study are taken from [6], the values of the weights α_k and β_j are from [6, 17].

The list of indicators taken into account, depending on the required accuracy of the estimate, can be extended (for example, by the values of criteria obtained by Prof. O.K.Byzyukov).

Table 4

Quality indicators of the compared samples

Indicator	Object				Values α_k и β_j
	E_1	E_2	E_3	E_4	
Technological, points	6	6	7	6	0,3
Degree of automation, points	8	6	7	8	0,25
Responsibility, scores	7	4	7	8	0,2
Ergonomics, points	6	6	6	7	0,04
Degree of standardization and unification, points	6	2	4	6	0,1
Aesthetic qualities, points	4	2	3	4	0,03
Specific weighted average emissions of toxic components with exhaust gases at rated power, g/kWh:					
Nitrogen oxides	6.2	15	13	11.2	0.02
Carbon oxide	0.5	3.4	0.4	0.6	0.02
Hydrocarbons	0.2	0.2	1	0.3	0.02
The sum of additional quality indicators taking into account their weight coefficients, scores	6.6	5	6.4	6.8	0.02
Assigned resource before overhaul, thou. hrs	60	55	40	45	–
Operating costs, cond. units st.	15	17	18	17	–
Cost (price), cond. units st.	37	31	35	37	–

According to the accepted methodology [13], in order to calculate the integral quality index, it is necessary to calculate the total useful effect (E_u) from operation for the whole service life, expressed in natural units. To do this, we find the useful effect of the estimated ETC, which differs from the baseline (E_{base}) for six measurable and seven unmeasured quality indicators, using the formula

$$E_1 = E_{\text{base}}\left\{1 + \sum_{k=1}^{3}\alpha_k \frac{\Delta P_k}{\Delta P_{\text{base}\ k}} + \sum_{j=1}^{7}\beta_j \frac{\Delta P_j}{P_{\text{base}\ j}}\right\},$$

where α_k – is the coefficient calculated by the expert method; β_j – is the coefficient calculated by the experimental method; ΔP_j – increment of the j th quality index of the ETK ($\Delta P_j = P_j - P_{\text{base}\,j}$); $P_{\text{base}\,j}$ – j-th non-measurable quality index of the basic ETC; ΔP_k is the increment of the k-th quality index of the ETK ($\Delta P_k = P_k - P_{\text{base}\,k}$); $P_{\text{base}\,k}$ – the k-th measured quality index of the basic ETC.

Note that the condition

$$\sum_{k=1}^{3}\alpha_k + \sum_{j=1}^{7}\beta_j = 1.$$

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If the capital costs are entered in the calculation year and the operating costs for the years remain constant, then the calculated costs are calculated using the following expression:

$$OC_{ac\,t} = TC + OC_i \frac{(1+E_n)^{t-1}}{E_n},$$

$$OC_t = \sum_{i=1}^{t} OC_i (1+E_n)^{i-1-t},$$

where OC_i – operational costs, carried out in the i-th year.

In other cases, the reduced costs are calculated as

$$RC_t = \mathrm{TC}(1-E_n)^{-t} + \sum_{i=1}^{t} OC_i (1+E_n)^{i-1-t}$$

In the general case, the integral quality score is determined on the basis of the following expression [11]:

$$I(t) = \frac{E_u}{TC + OC_i},$$

where E_u – the total useful effect from operation for the whole service life, expressed in natural units.

The total useful effect from the operation of the products for the entire service life t in the case when the annual effect P_1 is the same is calculated by the formula

$$E_u = \sum_{i=1}^{t} E_i = E_1 t,$$

where t – the time from the moment of investment of capital expenditures to the calculated year, years.

In Example 1, it was proved that the engines under consideration are divided into two separate classes according to the characteristics being compared, the first includes engines numbered one, three and four, and the engine number two must be considered separately. Therefore, the engine E_2 will be considered basic, its useful effect is taken to be unity. The results of the calculations are given in Table 5.

The useful effect of the engine E_1 is 1.44. This means that its useful effect is 1.44 times higher than the base engine E_2. Despite the fact that the E_4 engine had a useful effect of 1.52, the total useful effect of the engine E_1 (given the designated resource before overhaul) is almost 27 % higher.

Table 5

The results of calculating the value of the integral quality index

Indicator	Object			
	E_1	E_2	E_3	E_4
Useful effect E_1	1.440941	1	1.421953	1.515663
Total useful effect E_u	9.86946	6.278539	6.492936	7.785939
Reduced costs RC_t, cond. units st.	69.08736	60.27277	53.0255	61.99276
Integral quality score $I(t)$, 1/ cond. units st.	0.142855	0.104169	0.122449	0.125594
Change (quality index)	+	–	+	+

The integral indicator of the technical level of the engine E_1 above the base E_2 in 1.4 times, although the resulted costs for its creation are higher than for the base image.

Conclusion. Thus, the comprehensive assessment of the technical level of the prospective ETC mathematically proved both the technical and economic feasibility of the development of an ETC including an ICE of this type (E_1), and the scientific and methodological apparatus described allows one to take into account the influence of various factors.

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