

*It was proposed to improve the existing method of determining the quality of interaction of the elements of the subsystems of the Machine Operator-Machining Center-Control Program for manufacturing parts (MO-MC-CP) system. This method combines estimates of social (machine operator), technical (machining center), and informational (control program for manufacturing parts) subsystems. Improvements were achieved through the use of four independent indices which are defined separately. One index takes into account single, double and triple interactions of integrated indicators where values of specific weight of weight coefficients depend on the sample size. The other three indices are a synergistic effect where the weight coefficients do not depend on the sample size. Therefore, the model of this index was modified at the expense of additional subsystems.*

*Existing approaches to determining the indices are not focused on the assessment of the quality of interaction of the MO-MC-CP system, have software limitations, and work with limited sample sizes. With this in mind, it was decided to improve the existing tools of determining the quality indices of interaction to assess levels of interaction of the subsystem elements.*

*The proposed software-implemented methods and the technology of index assessment improve the efficiency of the assessment of complex systems. Experimental verification has shown the superiority of interaction quality indices over those in the existing methods. A sign of efficiency is as follows: a smaller value of mean-square deviation of the proposed indices in comparison with the existing ones:  $S(I_{Q1})=0.812$ ;  $S(I_{Q2})=0.271$ ;  $S(I_{Q3})=0.675$ ;  $S(I_{Q4})=0.57$  and  $S(I)=0.947$ ;  $S(I)=0.833$ ;  $S(I)=0.594$ , respectively.*

*The results obtained in the study of the interaction quality index are useful and important because they make it possible to better assess the interaction of subsystem elements and apply the proposed technology at industrial enterprises*

**Keywords:** *man-machine system, technology of determining interaction, means of index assessment, assessment conditions*

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# IMPROVING THE METHODS FOR DETERMINING THE INDEX OF QUALITY OF SUBSYSTEM ELEMENT INTERACTION

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## 1. Introduction

The process of determining the quality of interaction of man-machine systems is improved through information systems. Instructions on man-machine interaction in a particular environment including automation in a service field are given in [1]. The result of the man-machine interaction study consists in the development of new hardware and software [2] where the level of interaction increases due to designing new or improving existing software architectures [3]. The process of studying the quality of man-machine interaction involves the study of the structure of user-technology interfaces [4].

Despite the development of technologies, problems arise with the social component of the system where machine operators have different training levels. This factor reduces the level of quality of man-machine interaction. This problem is solved using the technologies that involve assessment of interaction quality, the study of the dependence of quality criteria on worker's (machine operator) skills [5].

At the same time, the proposed scientific and research works do not take into account the peculiarities of assessing the quality of interaction of the Machine Operator-Machining Center-Control Program of part making (MO-MC-CP) system. Limitations are related to the mathematical apparatus and software with functionality that does not take into account the interaction of factors of the subsystem elements and the synergistic effect.

Therefore, it is important to develop new and improve existing methods of determining the man-machine interaction and their implementation using software means.

## 2. Literature review and problem statement

The results obtained in the study of determining the interaction of complex systems are presented in [6]. It was shown that only the psychological state of a man interacting with other elements of subsystems is taken into account. However, this is not enough to assess the interaction quality because assessment of other subsystems is neglected.

The results obtained in [7] make it possible to study the dependences of influence of ergatic systems on a personality condition. However, the paper insufficiently considers the study of the impact of assessment results on the decision-making process.

In addition to psychophysiological properties, the models of assessment of the quality of interaction of the subsystem elements take into account the number of tasks performed by the machine operator [8]. The models proposed in [8] do not provide for determining the interaction of the MO-MC-CP system using primary estimates and an ordinal five-point scale.

According to the life cycle of the model, the modeled source data are used in the process of creating a complex system model. Only elucidation of general theoretical and methodological bases of determining man-machine interaction is a limitation

of [9]. It is unclear how the quality of interaction of the machine operator with other subsystems of a complex system is assessed.

Models of group interaction of operators of man-machine systems by means of tools from the theory of automatic control are described in [10]. Since the MO-MC-CP system assumes the presence of only one operator, the approach proposed in [10] requires additional studies by modifying the MO-MC-CP system which has not yet been fully studied.

Dependence of influence of weight coefficients calculated using different approaches on the level of a complex system index is studied in [11]. Suggestions for calculating the index using a model of linear convolution using certain restrictions on indicators and weights are shown. The study has resulted in the establishment of the subjectivity of expert methods which should be minimized. However, the problem of determining the weight coefficients, not based on the studied sample remained unresolved.

When determining the quality of man-technical means interaction, both known models of units and models which take into account the time spent on certain operations are used in automation [12]. At the same time, other indicators of interaction quality are used: reliability, accuracy, readiness factor, load factor, queue factor, speed, information capacity [13]. The problem of program realization of ideas remains insufficiently clear [12, 13].

The issue of assessment of the quality of human operator-machine interaction with the help of simulation technologies is considered in [14]. Simulation technologies make it possible to obtain just expert estimates which cannot be combined into indices or integrated indicators.

A method of using the Industrial Internet of Things is proposed in [15] with taking into account peculiarities of the Industrial Revolution 4.0. This method collects data from humans and automated equipment to study the human impact on industrial systems. The technologies described in [15] are quite complex and complicate the software development process. They insufficiently take into account the level of complexity of the production control software.

The study of control and temporal changes in socio-technical systems was studied in [16]. Theoretical and methodological bases of analysis of these systems are offered on the example of unmanned complexes where a much wider system than MO-MC-CP is considered.

For example, operator interfaces were differentiated depending on the level of the operator's skills [17] and recommendations on improving the level of man-machine interaction were given. This partially copes with the existing difficulties in assessing the level of quality of interaction because the study [17] did not consider the issue of index assessment.

According to [18], man-automation interaction is associated with the influence of subjective factors. The general analytical review given in [18] makes it possible to obtain certain positive results on the existence of subjectivism but does not address the issue of assessing the technologies and implementation of these technologies using the software.

According to the results of a study of man-machine interaction, the operator is considered as a head of several machines and a suitable model is proposed in [19]. The proposed model improves the definition of interaction level, however, the operator controls several machines but his interaction with the information subsystem is not studied.

The issue of improving the algorithms of automatic generation of minimally mental models using the methods of supporting the design of man-machine interaction systems was

studied in [20]. The proposed methodology [20] was software implemented, however, the mathematical model has limitations regarding the cooperation with social, technical, and information subsystems of MO-MC-CP systems. The problem of improving the index of quality of interaction of elements of subsystems of a complex system is also not considered.

Therefore, the issues of improving the index of quality of interaction of subsystem elements through the development of mathematical tools and software implementation of the tools in relevant software remain unresolved. This can be explained by the difficulty associated with the lack of a perfect mathematical apparatus and software. The models of the proposed approaches involve the use of only primary estimates or indices that are not unified. Improvement of existing tools for determining indices, development of the index assessment technology implemented in software may be an option of overcoming the existing difficulties.

Such approaches are used in [21]. According to the study results, tools of the decision theory and artificial intelligence for determining man-machine interaction are given. All of them are too complex to study and evaluate the MO-MC-CP system.

The abovementioned suggests that it is appropriate to conduct a study to improve approaches to assessing the quality of interaction of subsystem elements of the MO-MC-CP system and other complex systems built on its basis.

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### 3. The aim and objectives of the study

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The study objective consists in improving the existing tools and creating technology for determining the index of quality of interaction of elements of subsystems of the MO-MC-CP system and other systems. This will allow industrial enterprises to assess the level of quality of interaction of machine operators with machining centers and the programs controlling the part manufacture and use all this in decision-making processes.

To achieve this objective, the following tasks were set:

- improve the existing index of quality of subsystem element interaction;
- check the adequacy of the proposed index models;
- prove the advantages of proposed indices of quality of interaction over existing approaches;
- develop a technology of index assessment;
- experimentally verify the proposed approach.

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### 4. The study materials and methods

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The study of the existing index of quality of interaction of subsystems elements involved elucidation of the possibility of improving the existing index in such a way as to obtain a gain in the signs of efficiency. Interaction of the studied complex system was considered in the aspects of single, double and triple interaction of subsystem elements and synergetic effect.

The mathematical formulation of the problem implies the development of a method of describing the MO-MC-CP system and other systems to determine the quality of interaction of subsystem elements and has the following conditions.

*Condition 1.* The system consists of three subsystems: social (machine tool operator), technical (machining center), and informational (control program of part manufacture). To take into account the influences of external and internal factors, the MO-MC-CP system is modified based on the safety and motivation subsystems. In the case of using four sub-

systems, there is Machine Tool-Machining Center-Control Program of parts manufacture-Safe Environment system. To study the additional motivational component, a system called Machine Operator-Machining Center-Control Program of parts manufacture-Safe Environment-Motive was formed.

*Condition 2.* The above subsystem elements can be assessed using a five-point ordinal scale for which the following notation was proposed:  $X_1, X_2, X_3, X_4, X_5$ .

*Condition 3.* The model of linear convolution of the index determination where it is necessary to normalize variables and determine the weights giving one when added using a five-point ordinal is the initial model.

*Condition 4.* The studied index describing the interaction of three subsystems is limited to the use of three primary estimates  $X_1$ – $X_3$  in contrast to the existing complex (ergatic) systems where there are two or more operators. Description of the interaction of four subsystems is limited to the use of  $X_1$ – $X_4$  estimates and that for five subsystems is limited to the use of  $X_1$ – $X_5$  estimates.

The theoretically described mathematical model of the interaction quality index will be subjected to checking for adequacy according to the following known subproblems. Formulation of the problem. Let  $I_{QI1}, I_{QI2}, \dots, I_{QIi}$  is a theoretical sample. The general problem of the study consists in proving the adequacy of indices of quality of interaction of subsystem elements ( $I_{QI1}$ ), ( $I_{QI2}$ ), ( $I_{QI3}$ ), ( $I_{QI4}$ ). To solve the general problem, it is necessary to solve its subproblems.

Step 1. Determine the presence of systematic error with a confidence level  $\alpha=0.95$ .

Step 2. Determine the direction of distribution of index estimates.

Step 2. 1. Sort the index estimates of the sample as follows:  $I_{QI_{min}}=I_{QI1}<I_{QI2}<\dots<I_{QIi}=I_{QI_{max}}$ .

Step 2. 2. Go from the theoretical sample  $I_{QI1}, I_{QI2}, \dots, I_{QIi}$  to the statistical array of  $I_{QI(1)}, I_{QI(2)}, \dots, I_{QI(i)}$  in order to form an interval array of index estimates.

Step 2. 3. Determine the number of intervals of the studied index estimates of the theoretical sample.

Step 2. 4. Determine the width of the intervals.

Step 2. 5. Determine frequencies and relative frequencies of index assessment using the values of interval width.

Step 2. 6. Construct an empirical distribution function for an interval series.

Step 3. Check hypothesis  $H_0$  of the distribution type (normal, exponential, or other) using appropriate methods and construct a histogram of distribution and a probability graph of distribution.

Step 4. Determine the mean-square deviation.

It was proposed to prove the advantages of the proposed method by comparing the mean-square deviation of the studied approach and the known method of linear convolution.

To conduct experimental verification, it was proposed to use the developed software tool of index assessment.

## 5. The results obtained in the study of the method of index of quality of interaction of subsystem elements

### 5. 1. The offered improved indices of quality of interaction of subsystem elements

#### 5. 1. 1. Improved indices of quality of interaction of elements of three subsystems

The formula of interaction quality index was derived in two stages (the years of 2019–2020) with the involvement

of leading specialists. Two indices were obtained. Symbols of indexes were introduced. The index of quality of interaction of subsystem elements taking into account single, double and triple interaction of integrated indicators was marked as ( $I_{QI1}$ ). The index of quality of interaction of subsystem elements taking into account the synergetic effect was marked as ( $I_{QI2}$ ).

According to the results of the first stage of the study carried out in 2019, the index of quality of interaction of subsystem elements taking into account single, double and triple interaction of integrated indicators ( $I_{QI1}$ ) was determined using the objective function (1) from [22]:

$$I_{QI1} = \sum_{i=1}^n (\lambda_1 \cdot I_{1i} + \lambda_2 \cdot I_{2i} + (1 - \lambda_1 - \lambda_2) \cdot I_{3i}) \rightarrow \max, \quad (1)$$

where  $\lambda_1$ – $\lambda_3$  are the weight coefficients of integrated indicators  $I_{1I}$ – $I_{3I}$ , respectively;

$I_{1I}$ – $I_{3I}$  are integrated indicators which are determined as follows:

$$I_{1i} = \frac{X_1 + X_2 + X_3}{3}, \quad I_{2i} = \sqrt{\frac{X_1X_2 + X_1X_3 + X_2X_3}{3}},$$

$$I_{3i} = \sqrt[3]{X_1X_2X_3},$$

where  $X_1, X_2, X_3$  are initial estimates of social, technical, and information subsystems.

The obtained formula makes it possible to investigate the quality of interaction of subsystem elements taking into account the single, double and triple interaction of integrated indicators.

According to the study results at the second stage (2020), the index of quality of interaction of subsystem elements taking into account the synergetic effect ( $I_{QI2}$ ) had the form (2) from [23]:

$$I_{QI2} = \lambda_1 X_1 + \lambda_2 X_2 + \lambda_3 X_3 + \lambda_4 W_1 + \lambda_5 W_2 + \lambda_6 W_3 + \lambda_7 W_4, \quad (2)$$

where  $\lambda_1$ – $\lambda_7$  are values of specific weight of the weight coefficients;

$X_1$  is the estimate of the social subsystem;

$X_2$  is the estimate of the technical subsystem;

$X_3$  is the estimate of the informational subsystem;

$W_1$ – $W_4$  are the indicators belonging to the set [1, 5].

It was proposed to determine the weight coefficients  $\lambda_1$ – $\lambda_7$  regardless of the sample size according to the formed criteria using the method of hierarchy analysis [24].

Thus, two indices of quality of interaction of subsystem elements describing three subsystems were offered. These indices are used separately from each other depending on the study objectives.

### 5. 1. 2. Improved models of indices of quality of interaction of elements of four and more subsystems

Taking into account four or more elements of subsystems in determining the quality of their interaction gives rise to the formation of a new complex system. In this regard, it was proposed to take into account the fourth (safety) and fifth (motivational) subsystems. The models were found on the basis of the existing formula [23].

The model of the index of quality of interaction with four subsystem elements ( $I_{QI3}$ ) was found in (3):

$$I_{QI3} = \lambda_1 X_1 + \lambda_2 X_2 + \lambda_3 X_3 + \lambda_4 X_4 + \lambda_5 W_1 + \lambda_6 W_2 + \lambda_7 W_3 + \lambda_8 W_4 + \lambda_9 W_5 + \lambda_{10} W_6 + \lambda_{11} W_7, \quad (3)$$

where  $\lambda_1$ – $\lambda_{11}$  are the value of specific gravity of the weight coefficients;

- $X_1$  is the estimate of the social subsystem;
- $X_2$  is the estimate of the technical subsystem;
- $X_3$  is an estimate of the information subsystem;
- $X_4$  is the estimate of the safety subsystem;
- $W_1$ – $W_7$  are the indicators belonging to the set [1, 5].

The model of the index of quality of interaction with five subsystem elements ( $I_{QI4}$ ) was determined in (4):

$$I_{QI4} = \lambda_1 X_1 + \lambda_2 X_2 + \lambda_3 X_3 + \lambda_4 X_4 + \lambda_5 X_5 + \lambda_6 W_1 + \lambda_7 W_2 + \lambda_8 W_3 + \lambda_9 W_4 + \lambda_{10} W_5 + \lambda_{11} W_6 + \lambda_{12} W_7 + \lambda_{13} W_8 + \lambda_{14} W_9 + \lambda_{15} W_{10} + \lambda_{16} W_{11}, \quad (4)$$

where  $\lambda_1$ – $\lambda_{16}$  is the value of the specific weight of weight functions;

- $X_1$  is the estimate of the social subsystem;
- $X_2$  is the estimate of the technical subsystem;
- $X_3$  is the estimate of the informational subsystem;
- $X_4$  is the estimate of the safety subsystem;
- $X_5$  is the estimate of the motivational subsystem;
- $W_1$ – $W_{11}$  are the indicators belonging to the set [1, 5].

In contrast to the index of quality of interaction of the elements of three subsystems ( $I_{QI2}$ ), the obtained models ( $I_{QI3}$ ), ( $I_{QI4}$ ) differ in the number of variables and weight coefficients. The model ( $I_{QI3}$ ) has  $5^4=625$  possible combinations of estimates  $X_1$ – $X_4$  where each estimate has five variants. The model ( $I_{QI4}$ ) is characterized by the maximum number of combinations of estimates  $X_1$ – $X_5$ ;  $5^5=3125$ . This series of estimates were used to study the adequacy of the models.

## 5.2. Proof of adequacy of the proposed indices of quality of interaction of subsystem elements

### 5.2.1. Proof of adequacy of the proposed indices of quality of interaction of three elements of subsystems

The next stage of the model life cycle involves the study of its adequacy [25]. Therefore, we will study the adequacy of the two proposed quality indices of the interaction of three elements of subsystems ( $I_{QI1}$ ), ( $I_{QI2}$ ).

The process of identifying the adequacy of the index of quality of interaction of subsystem elements involved the presence of primary estimates of elements of social (machine operator),  $X_1$ , technical (machining center),  $X_2$ , informational,  $X_3$ , subsystems. Using combinatorics for the index of quality of interaction of subsystem elements which takes into account the synergetic effect, the maximum possible number of series of primary estimates makes 125 combinations. This number of combinations of primary estimates was also used to determine the index of quality of interaction of subsystem elements taking into account single, double and triple interaction of integrated indicators. Thus, the quality of interaction of three subsystem elements of the MO-MC-CP system was described by two proposed indices. Actually, 125 combinations of primary estimates allowed us to obtain a theoretical sample of  $n=125$  of the MO-MC-CP systems, Table 1.

Using the values of indices of quality of interaction of subsystem elements of the system ( $I_{QI1}$ ), ( $I_{QI2}$ ) from Table 1, investigate their adequacy by the methods of mathematical statistics [25].

Table 1

Primary estimates of  $X_1$ – $X_3$  subsystem elements and values of indices of quality of interaction of subsystem elements of the  $I_{QI1}$ ,  $I_{QI2}$  system

No.	$X_1$	$X_2$	$X_3$	$I_{QI1}$	$I_{QI2}$
1	1	1	1	1.00	1.000
2	2	1	1	1.33	1.205
3	3	1	1	1.67	1.410
...	...	...	...	...	...
124	4	5	5	4.67	4.479
125	5	5	5	5.00	5.000

Consider the steps of solving subproblems, see Steps 1–4.

Step 1. Determining the adequacy of obtained series of quality indices of the interaction of subsystem elements of the system ( $I_{QI1}$ ), ( $I_{QI2}$ ) involves exclusion of systematic error.

The presence of systematic errors was identified in this study using a known statistical method: single-factor variance analysis with a confidence level of  $\alpha=0.95$ . Solution of the formed problem involves checking of two hypotheses:  $H_0$  on the existence of the factor influence on the experiment result and  $H_1$  on equality of group averages. The results of the calculation of one-way variance analysis are presented in Table 2.

Table 2

Summary results of calculation of one-factor variance analysis with confidence probability  $\alpha=0.95$  of a number of estimates of indices of quality of interaction of elements of subsystems of the system ( $I_{QI1}$ ), ( $I_{QI2}$ ) obtained on the basis of combinations of primary estimates  $X_1$ – $X_3$

The studied values of the index of quality of interaction of subsystem elements taking into account single, double and triple interaction of integrated indicators ( $I_{QI1}$ )					
$\sum I_{QIi}$	$\bar{I}_{QI}$	$\sum I_{QIij}^2$	$S_{All}$	$S_F$	
375	3.0	1208.34	83.34	0	83.34
$S_f^2$	$S_r^2$	$F_n$	$f_k$ at $\alpha=0.05$		–
0	0.67	0	3.84		–
The studied values of the index of quality of interaction of subsystem elements taking into account the synergetic effect ( $I_{QI2}$ )					
$\sum I_{QIi}$	$\bar{I}_{QI}$	$\sum I_{QIij}^2$	$S_{All}$	$S_F$	$S_r$
315.72	2.52	880.36	82.9	0	82.9
$S_f^2$	$S_r^2$	$F_n$	$f_k$ at $\alpha=0.05$		–
0	0.66	0	3.84		–

According to the results of the study of the single-factor variance analysis, it was found that the group averages differ slightly at a confidence level  $\alpha=0.95$ . Therefore, the hypothesis of the existence of factor influence on the experimental result was omitted and the hypothesis of equality of group averages was accepted. That is, the presence of systematic error in the studied series of estimates of quality indices of the interaction of subsystem elements of the system ( $I_{QI1}$ ), ( $I_{QI2}$ ) was not detected.

Step 2. The absence of systematic error is a prerequisite for determining the direction of distribution of the studied sample of index estimates by constructing an empirical function of distribution, see Steps 2. 1–2. 6.

Step 2. 1. The subproblem 2. 1 is solved by sorting index estimates from  $I_{Q1min}$  to  $I_{Q1max}$  separately of two series of indices ( $I_{Q1}$ ), ( $I_{Q2}$ ). The obtained series of sorted index estimates are used to form a statistical series.

Step 2. 2. To solve subproblem 2. 2, take into account the content and structure of the statistical series. So, as there is a question of the creation of intervals of the investigated sample, we will group them and obtain the grouped statistical series (interval series).

Step 2. 3. Determine the number of studied groups separately for the two studied indices of quality of interaction of the subsystem elements according to the Sturges formula  $1+3.322\log(125)=8$ . Having obtained the number of studied groups of MO-MC-CP systems described by the indices of quality of interaction of subsystem elements, the interval width can be determined.

Step 2. 4. Since we have a five-point ordinal scale, then the width of the interval can be determined where  $h=5-1/8=0.5$ . The obtained value of the interval width is used to form actual intervals of index estimates.

Step 2. 5. Subproblem 2.5 regarding the definition of intervals, frequency, and relative frequency is solved as follows, Table 3.

**Table 3**  
Determining the intervals, frequency, and relative frequency of the studied indices

The studied intervals	$(I_{Q1})$		$(I_{Q2})$	
	Frequency	Relative frequency	Frequency	Relative frequency
1.0–1.5	4	4/125=0.032	11	11/125=0.088
1.5–2.0	6	6/125=0.048	26	26/125=0.208
2.0–2.5	25	25/125=0.2	32	32/125=0.256
2.5–3.0	18	18/125=0.144	23	23/125=0.184
3.0–3.5	37	37/125=0.296	15	15/125=0.12
3.5–4.0	15	15/125=0.12	10	10/125=0.08
4.0–4.5	16	16/125=0.128	6	6/125=0.048
4.5–5.0	4	4/125=0.032	2	2/125=0.016
Total	125	1.00	125	1.00

The defined studied intervals, frequencies, and relative frequencies form the basis for constructing the empirical function of the distribution of both indices.

Step 2. 6. Subproblem 2. 6 regarding the construction of the empirical function of the studied distribution is solved as follows, Table 4.

Empirical functions of distribution of indices ( $I_{Q1}$ ), ( $I_{Q2}$ ) indicate the existence of directionality of the normal distribution law for series of index estimates.

Step 3. Support of the normal distribution condition for the theoretically formed sample  $n=125$  units of estimates of indices of quality of interaction of subsystem elements ( $I_{Q1}$ ), ( $I_{Q2}$ ) is determined according to the Kolmogorov-Smirnov criterion. The following results were obtained using initial estimates of the indices ( $I_{Q1}$ ), ( $I_{Q2}$ ) given in Table 1 where the significance level  $\alpha$  is greater than 0.2. Therefore, the hypothesis of normality of distribution is not rejected, Fig. 1.

Fig. 2 shows the results of studies of the index of interaction quality which takes into account the synergistic effect of  $I_{Q2}$  of the theoretical sample with  $n=125$  units where the probability distribution graph is constructed.

**Table 4**

Empirical function of distribution of indices ( $I_{Q1}$ ), ( $I_{Q2}$ )

The empirical function of distribution of the index ( $I_{Q1}$ )	The empirical function of distribution of the index ( $I_{Q2}$ )
$F_{(x)}^* = \begin{cases} 0, & x = 1, \\ 0 + 0.032 = 0.032, & x = 1.5, \\ 0.032 + 0.048 = 0.08, & x = 2.0, \\ 0.08 + 0.2 = 0.28, & x = 2.5, \\ 0.28 + 0.144 = 0.424, & x = 3.0, \\ 0.424 + 0.296 = 0.72, & x = 3.5, \\ 0.72 + 0.12 = 0.84, & x = 4.0, \\ 0.84 + 0.128 = 0.968, & x = 4.5, \\ 0.968 + 0.032 = 1.0, & x = 5.0 \end{cases}$	$F_{(x)}^* = \begin{cases} 0, & x = 1, \\ 0 + 0.088 = 0.088, & x = 1.5, \\ 0.088 + 0.208 = 0.296, & x = 2.0, \\ 0.296 + 0.256 = 0.552, & x = 2.5, \\ 0.552 + 0.184 = 0.736, & x = 3.0, \\ 0.736 + 0.12 = 0.856, & x = 3.5, \\ 0.856 + 0.08 = 0.936, & x = 4.0, \\ 0.936 + 0.048 = 0.984, & x = 4.5, \\ 0.984 + 0.016 = 1.0, & x = 5.0 \end{cases}$

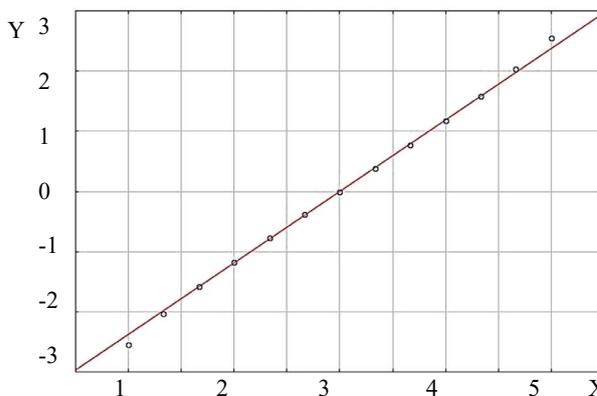


Fig. 1. The results of studies of the index of quality of interaction of the subsystem elements taking into account single, double and triple interaction of the integrated indicators  $I_{Q1}$  of a theoretical sample with  $n=125$  units

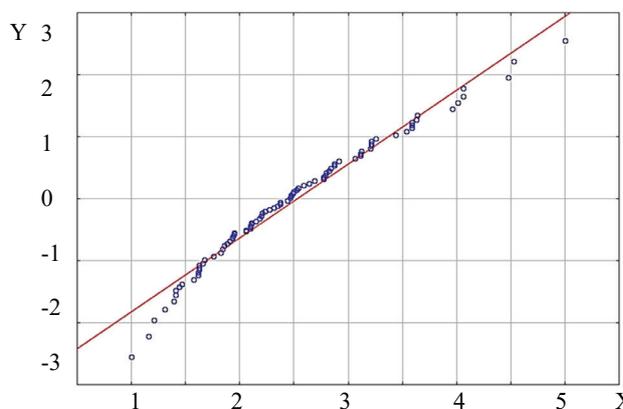


Fig. 2. The results of studies of the interaction quality index taking into account the synergistic effect of  $I_{Q2}$  of a theoretical sample with  $n=125$  units

The probabilistic graph of distribution, Fig. 1, confirms support of the normal distribution condition. However, small spikes are observed in the lower and upper parts on the probability graph in Fig. 2. They are associated with errors in input estimates.

Step 4. Mean-square deviation of estimates of indices of quality of interaction of the subsystem elements ( $I_{Q1}$ ), ( $I_{Q2}$ ) is determined. Estimates of mean-square deviation are  $S(I_{Q1})=0.82$ ;  $S(I_{Q2})=0.073$ , respectively.

Thus, according to the experimental results, adequacy of the indices of quality of interaction of elements of three subsys-

tems, ( $I_{Q1}$ ), ( $I_{Q2}$ ), was proved. This is evidenced by the equality of group averages and the existence of a condition of normal distribution. Estimate of standard deviation will be used as a criterion for determining the accuracy of developed indices of quality of interaction of subsystem elements, ( $I_{Q1}$ ), ( $I_{Q2}$ ).

**5. 2. 2. Proving the adequacy of models of indices of quality of interaction of four or more subsystem elements**

Adequacy of indices of quality of interaction of four or more subsystems was proved using the technology applied to the indices of quality of interaction with three subsystems [25]. Since these indices ( $I_{Q3}$ ), ( $I_{Q4}$ ) have a different maximum number of estimate series (625 and 3125, respectively), individual diagnosis of adequacy should be performed for each.

According to the results obtained in the study of systematic error, step 1, by the method of single-factor variance analysis with confidence probability  $\alpha=0.95$  for the indices ( $I_{Q3}$ ), ( $I_{Q4}$ ), it was not detected.

Step 2. The determined empirical functions of distribution of indices ( $I_{Q3}$ ), ( $I_{Q4}$ ) demonstrate the vector of distribution directionality. For the samples of ( $I_{Q3}$ ), ( $I_{Q4}$ ) estimates, the condition of normal law is supported which is confirmed at the level of significance  $\alpha$  greater than 0.2 by the Kolmogorov-Smirnov criterion, step 3.

Step 4. The value of standard deviation  $S(I_{Q3})=0.695$ ;  $S(I_{Q4})=0.618$  is established.

**5. 3. Proof of the advantage of indices of quality of interaction of subsystem elements over known integrated indicators**

**5. 3. 1. Proof of the advantage of indices of quality of interaction of three subsystem elements**

Advantage of the indices of quality of interaction of subsystem elements,  $I_{Q1}$ ,  $I_{Q2}$ , Table 1, over known integrated indicators was proved according to the criterion of minimum standard deviation. The model of linear convolution (5) [24] was chosen as the basis of the model of known index:

$$y=k_1x_i+k_2y_i+k_3z_i, \tag{5}$$

where  $k_1-k_3$  are variables;  $x_i, y_i, z_i$  are weight coefficients.

Variables  $k_1-k_3$  of linear convolution were calculated on the basis of primary estimates of the subsystem elements,  $X_1-X_3$ , Table 1. Weight coefficients  $x_i, y_i, z_i$  were chosen by a known enumerative technique in the coordinate plane where the sum of specific weights of the weight coefficients is equal to 1.0. Possible values of specific weights of the weight coefficients are given in Table 5.

Table 5

Combinations of specific weights of weight coefficients  $x_i, y_i, z_i$

$i$	$x_i$	$y_i$	$z_i$	$i$	$x_i$	$y_i$	$z_i$
1	0.2	0.2	0.6	6	0.4	0.4	0.2
2	0.2	0.4	0.4	7	0.4	0.6	0
3	0.2	0.6	0.2	8	0.6	0.2	0.2
4	0.2	0.8	0	9	0.6	0.4	0
5	0.4	0.2	0.4	10	0.8	0.2	0

The combinations of specific weights of weight coefficients given in Table 5 were alternately substituted in the model of linear convolution. However, the fourth, seventh, ninth and tenth combinations of specific weights were not

used because one of the specific weights is zero. Values of the indices obtained using the method of determination of linear convolution are shown in Table 6.

Table 6

The series of indices obtained on the basis of initial estimates of the subsystem elements,  $X_1-X_3$ , and various combinations of numerical values of specific weights

No.	$I_1$	$I_2$	$I_3$	$I_5$	$I_6$	$I_8$
1	1	1	1	1	1	1
2	1.2	1.2	1.2	1.4	1.4	1.6
...	...	...	...	...	...	...
124	4.8	4.8	4.8	4.6	4.6	4.4
125	5	5	5	5	5	5
$\Sigma$	375	375	375	375	375	375
Mean-square deviation						
$S$	0.94	0.85	0.94	0.85	0.85	0.94

As can be seen from Table 6, when values of coefficients of specific weight change, the index formula changes, and new values of index estimates are formed. The total value of the series of indices found using the method of linear convolution is the same, amounting  $\Sigma y=375$ . However, values of the mean-square deviation differ for each series of indices. The smallest value of the mean-square deviation  $S=0.85$  was achieved for indices  $I_2, I_6$  when numerical specific weight values of 0.2; 0.4; 0.4 and 0.4; 0.4; 0.2, respectively, were used. Indices  $I_1, I_3, I_8$  had the greatest value of mean-square deviation at weight coefficients 0.2; 0.2; 0.6; 0.2; 0.6; 0.2 and 0.6; 0.2; 0.2.

It is known from the theoretical and methodological premise of the study that indices with minimum mean-square deviation show more accurate results. The indices  $I_2, I_5, I_6$  had minimum mean-square deviation  $S=0.85$ . Therefore, to compare the index calculated based on the method of linear convolution with the index of quality of interaction of subsystem elements, it is advisable to choose a series of values of one of the indices  $I_2, I_5, I_6$ , Table 7.

Table 7

Comparative analysis of the known index calculated by the method of linear convolution and the proposed indices of quality of interaction of subsystems elements based on standard deviation

Index name	Mean-square deviation
The known index calculated on the basis of the method of linear convolution	$S=0.85$
The index of quality of interaction of subsystem elements taking into account single, double and triple interaction of integrated indicators ( $I_{Q1}$ )	$S=0.82$
The index of quality of interaction of subsystem elements taking into account the synergetic effect ( $I_{Q2}$ )	$S=0.073$

As can be seen from Table 7, the proposed indices ( $I_{Q1}$ ), ( $I_{Q2}$ ) prevail (based on standard deviation) over the known index.

**5. 3. 2. Proof of the advantage of indices of quality of interaction of four and five subsystem elements**

Two different sets of estimates were used to prove the advantage of the proposed index models describing the inter-

action of four and five subsystem elements. Initial estimates of  $X_1-X_4$  (625 series) were used for the index of quality of interaction of four subsystems ( $I_{Q3}$ ) and estimates of  $X_1-X_5$  (3125 series) were used for five subsystems ( $I_{Q4}$ ).

The specific weight of weight coefficients for the indices of quality of interaction of four ( $I_{Q3}$ ) and five ( $I_{Q4}$ ) subsystem elements was taken averaged.

Values of 0.1; 0.2; 0.3; 0.4; 0.5 were chosen as a basis of the coefficients of specific weight of the known integrated indicator when all possible options of their placement were identified. Standard deviation of the known integrated indicator was  $S=0.849$  at values of weight coefficients 0,1; 0.3; 0.1; 0.5.

Table 8

Comparative analysis of the models of indices of quality of interaction of four and five subsystem elements with a known integrated indicator based on standard deviation

Index name	Mean-square deviation
Known index describing the interaction of four subsystems calculated on the basis of the method of linear convolution	$S=0.849$
Index of quality of interaction of four subsystem elements ( $I_{Q3}$ )	$S=0.695$
Known index describing the interaction of five subsystems calculated on the basis of the linear convolution method	$S=0.633$
Index of quality of interaction of five subsystem elements, ( $I_{Q4}$ )	$S=0.618$

According to the results of the comparative analysis of indices (Table 8), there is an advantage of the proposed models over the known ones.

**5. 4. Technology of index assessment of machine tool operators**

A technology of index estimate was proposed. Its purpose consists in estimating the indices of quality of interaction of subsystem elements ( $I_{Q1}$ ), ( $I_{Q2}$ ), ( $I_{Q3}$ ), ( $I_{Q4}$ ). The indices were measured on a five-point ordinal scale. Estimates of social, technical, informational, safety, and motivational subsystems were the initial estimates for starting this technology. Each index has its own features consisting of variables and weights which are determined separately. Weight coefficients of the index ( $I_{Q1}$ ) are determined by the enumerative technique in the coordinate plane and depend on the sample size. Weight coefficients of indices ( $I_{Q2}$ ), ( $I_{Q3}$ ), ( $I_{Q4}$ ) are determined by the method of analysis of hierarchies [24] irrespective of the sample size. A formed table of index estimates of systems is the final result of determining the indices ( $I_{Q1}$ ), ( $I_{Q2}$ ), ( $I_{Q3}$ ), ( $I_{Q4}$ ). The block diagram of the index assessment is given in Fig. 3.

The diagram structure provides for 18 components (blocks).

Block 1. The input of initial estimates of  $X_1-X_3$  and  $X_4, X_5$  if any. Objective characteristics are also recorded and the studied samples are formed from the set of entered estimates.

Block 2. Choice of a method of calculating the quality of interaction of three subsystem elements, ( $I_{Q1}$ ), ( $I_{Q2}$ ), or quality of interaction of four or more elements, ( $I_{Q3}$ ), ( $I_{Q4}$ ).

Block 3. Choice of a method of ( $I_{Q1}$ ) or ( $I_{Q2}$ ) calculation.

Block 4. Determination of the index of quality of interaction of subsystem elements taking into account single, double and triple interaction of integrated indicators ( $I_{Q1}$ ) provides calculation of variables  $I_{1i}, I_{2i}, I_{3i}$  and weight coefficients  $\lambda_1, \lambda_2, \lambda_3$ . The sum:  $\lambda_i=1$ .

Block 5. Checking objectivity of the calculated index ( $I_{Q1}$ ) estimates. If the calculation results satisfy the decision-maker, the calculation is considered complete. Otherwise, go to block 3 where another sample of machine operators is selected.

Block 6. Determination of weight coefficients  $\lambda_i$  by the method of analysis of index hierarchies ( $I_{Q2}$ ) according to the formed criteria  $C_{11}, C_{21}, C_{31}...C_{ni}$ , Table 9.

Table 9

Matrix of pairwise comparisons of combinations of subsystem elements according to  $C_i$  criteria

$C_1$	$S_1$	$T_2$	$I_3$	$ST_4$	$TI_5$	$SI_6$	$STI_7$
$S_1$	$X_{11}$	$X_{12}$	$X_{13}$	$X_{14}$	$X_{15}$	$X_{16}$	$X_{17}$
$T_2$	$X_{21}$	$X_{22}$	$X_{23}$	$X_{24}$	$X_{25}$	$X_{26}$	$X_{27}$
$I_3$	$X_{31}$	$X_{32}$	$X_{33}$	$X_{34}$	$X_{35}$	$X_{36}$	$X_{37}$
$ST_4$	$X_{41}$	$X_{42}$	$X_{43}$	$X_{44}$	$X_{45}$	$X_{46}$	$X_{47}$
$TI_5$	$X_{51}$	$X_{52}$	$X_{53}$	$X_{54}$	$X_{55}$	$X_{56}$	$X_{57}$
$SI_6$	$X_{61}$	$X_{62}$	$X_{63}$	$X_{64}$	$X_{65}$	$X_{66}$	$X_{67}$
$STI_7$	$X_{71}$	$X_{72}$	$X_{73}$	$X_{74}$	$X_{75}$	$X_{76}$	$X_{77}$

The determined weight coefficients are used in the ( $I_{Q2}$ ) index formula.

Block 7. Calculation of variables and the entire ( $I_{Q2}$ ) index formula using the values of weight coefficients determined in the previous block.

Block 8. if the obtained values are calculated objectively and do not need any adjustments to the weight coefficients or initial estimates, go to the next Block 9, otherwise, go to Block 3.

Block 9. Choice of the method of calculating the quality of interaction of the elements of four ( $I_{Q3}$ ) or five ( $I_{Q4}$ ) subsystems.

Block 10. Similar to block 6, weight coefficients for the ( $I_{Q3}$ ) index are determined.

Block 11. Calculation of the index of quality of interaction of four subsystem elements according to formula (3).

Block 12. If the calculated value of the ( $I_{Q3}$ ) index satisfies the decision-maker, then go to Block 11, otherwise Block 9.

Block 13. Similarly to Blocks 6, 10, weight coefficients are determined for the ( $I_{Q4}$ ) index.

Block 14. The index of the quality of interaction of five subsystem elements is calculated according to formula (4).

Block 15. If the calculated value of the ( $I_{Q4}$ ) index satisfies the decision-maker, then go to Block 16, otherwise, go to Block 9.

Block 16. The determined index estimates are displayed on the user interface.

Block 17. Enables moving to Block 18 where a report is generated or to Block 1 if adjustments of input estimates  $X_1-X_5$  are required.

Block 18. Generation of a report on the assessment of machine tool operators (Table 10).

If it is necessary to make comparisons, a summary table of all indices ( $I_{Q1}$ ), ( $I_{Q2}$ ), ( $I_{Q3}$ ), ( $I_{Q4}$ ) is generated, Table 11.

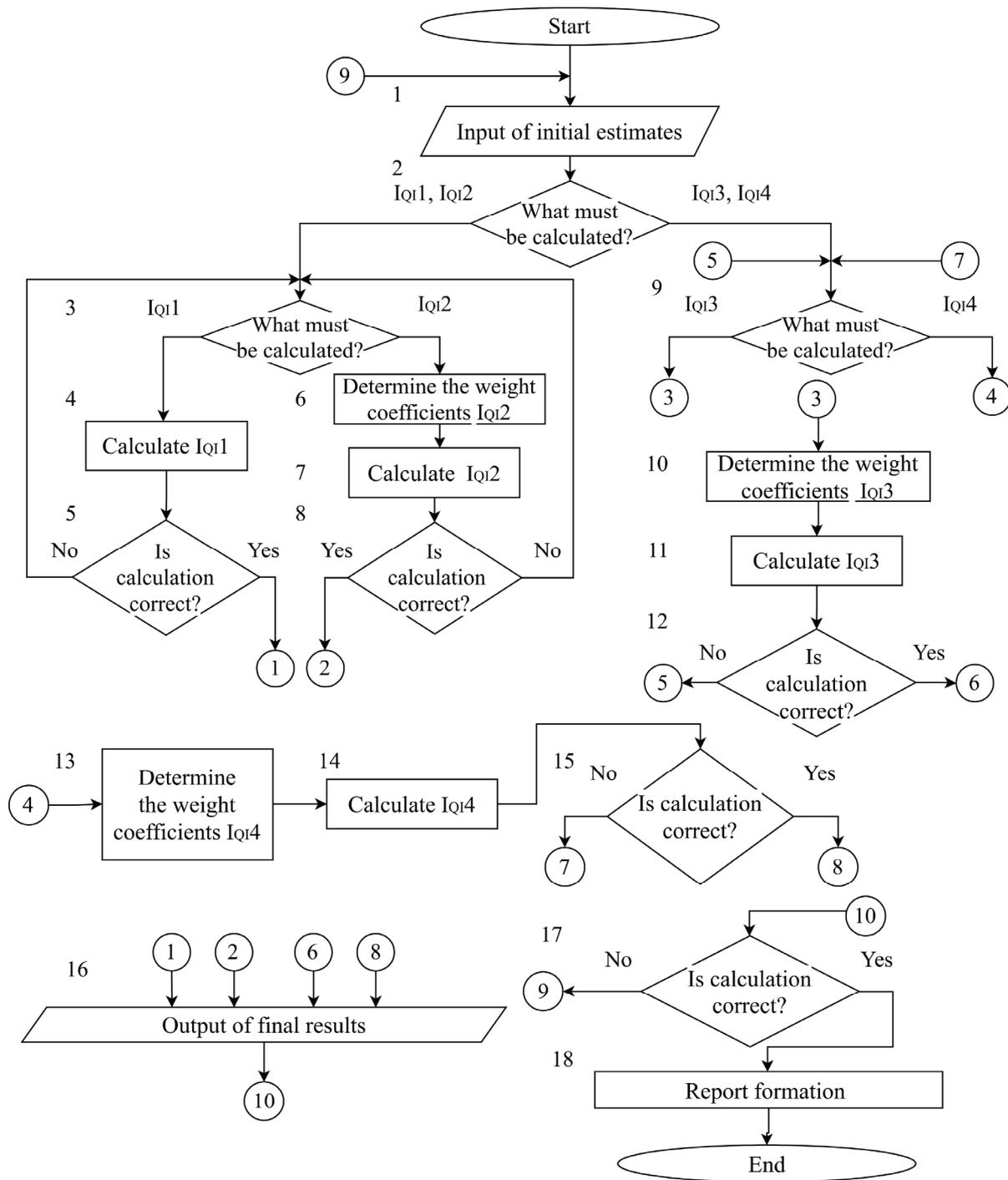


Fig. 3. Block diagram of the index assessment algorithm

Table 10

The results of index assessment of machine tool operators according to one of the studied indices

No.	Complex system	Level of index ( $I_{Qn}$ )
1	System 1	$I_{Q11}$
2	System 2	$I_{Q12}$
3	System 3	$I_{Q13}$
...	...	...
$n$	System $n$	$I_{Q1n}$

Thus, the reporting tables of the determined indices are generated in this way.

Table 11

Summary table of the results of index assessment of machine operators according to the studied indices ( $I_{Q1}$ ), ( $I_{Q2}$ ), ( $I_{Q3}$ ), ( $I_{Q4}$ )

No.	Complex system	Level of index ( $I_{Q1i}$ )	Level of index ( $I_{Q2i}$ )	Level of index ( $I_{Q3i}$ )	Level of index ( $I_{Q4i}$ )
1	System 1	$I_{Q111}$	$I_{Q211}$	$I_{Q311}$	$I_{Q411}$
2	System 2	$I_{Q112}$	$I_{Q212}$	$I_{Q312}$	$I_{Q412}$
3	System 3	$I_{Q113}$	$I_{Q213}$	$I_{Q313}$	$I_{Q413}$
...	...	...	...	...	...
$n$	System $n$	$I_{Q1n}$	$I_{Q2n}$	$I_{Q3n}$	$I_{Q4n}$

**5. 5. Experimental verification of the obtained results of index assessment**

**5. 5. 1. Preparation of software means of index assessment**

Experimental verification of the results obtained in the study involved the design and implementation of the proposed ideas of carrying out tests. For this purpose, the proposed algorithm was implemented in the php programming language using the MySQL database where the quality of interaction of subsystem elements was assessed by index methods for  $(I_{QI1}), (I_{QI2}), (I_{QI3}), (I_{QI4})$ .

The software functional involves determining the specific weights of weight coefficients  $\lambda_j$  and indices according to the criteria  $K_i$ . For example, the following criteria were proposed for  $(I_{QI2})$  (Table 12).

The list of criteria that was formed, Table 12, is recorded in software means and used to determine specific weights of weight coefficients. The obtained values of the specific weight of the weight coefficients  $\lambda_j$  are given in Table 13.

Table 12

The list of the formed study criteria for determination of weight coefficients  $\lambda_i$  of the index  $(I_{QI2})$  by the method of analysis of hierarchies

Criteria	Criterion content
$C_1$	Which of the subsystems, social or technical, affects the quality of interaction more significantly?
$C_2$	Which of the subsystems, technical or informational, affects the quality of interaction more significantly?
$C_3$	Which of the subsystems, social or informational, affects the quality of interaction more significantly?
$C_4$	Is the impact of the interaction of social+technical subsystems more significant than the impact of each subsystem separately?
$C_5$	Is the impact of the interaction of technical+informational subsystems more significant than the impact of each subsystem separately?
$C_6$	Is the impact of the interaction of social+informational subsystems more significant than the impact of each subsystem separately?
$C_7$	Is the impact of the interaction of social, technical+informational subsystems more significant than the impact of each subsystem separately?

Table 13

Indicators of specific weight calculated on the basis of the method of analysis of hierarchies used in the index of quality of interaction of subsystem elements  $(I_{QI2})$

Indicator	$X_1$	$X_2$	$X_3$	$W_1$	$W_2$	$W_3$	$W_4$
Weight coefficient	$\lambda_1$	$\lambda_2$	$\lambda_3$	$\lambda_4$	$\lambda_5$	$\lambda_6$	$\lambda_7$
Value	0.051	0.03	0.028	0.216	0.154	0.113	0.402

Thus, the following values of weight coefficients will be used in block 6 (Table 13). If necessary, it is possible to adjust criteria (Table 12) or values of the specific weight of weight coefficients (Table 13) at any stage of the study. Criteria for other indices  $(I_{QI3}), (I_{QI4})$  are generated in a similar way.

**5. 5. 2. Experimental verification of the proposed approach of index assessment**

Experimental verification of the assessment technology involved the use of the model of the general set of MO-

MC-CP system,  $N=541$ , generated at the previous stage of study [25]. A representative sample ( $n_d=225$ ) of the studied MO-MC-CP systems was formed with a confidence probability of 95 % and a confidence interval of  $\pm 5$  % [26].

In order to verify the assessment objectivity, estimates of  $X_1-X_5$  of the MO-MC-CP systems obtained in the first diagnostic section of 2021 were used and seven indices were experimentally determined on their basis (four proposed software implemented  $(I_{QI1}), (I_{QI2}), (I_{QI3}), (I_{QI4})$  and three known ones), Table 14.

Table 14

Experimental verification of the studied indices on the basis of standard deviation

Index name	Mean-square deviation
Known index calculated based on the method of linear convolution	$S=0.947$
Index of quality of interaction of subsystem elements taking into account single, double and triple interaction of integrated indicators $(I_{QI1})$	$S=0.812$
Index of quality of interaction of subsystem elements taking into account synergetic effect $(I_{QI2})$	$S=0.271$
Known index describing the interaction of four subsystems calculated on the basis of the method of linear convolution	$S=0.833$
Index of quality of interaction of four subsystem elements $(I_{QI3})$	$S=0.675$
Known index describing the interaction of five subsystems calculated on the basis of the method of linear convolution	$S=0.594$
Index of quality of interaction of five subsystem elements $(I_{QI4})$	$S=0.57$

The calculated indices of interaction quality, Table 14, and their comparative analysis on the basis of standard deviation experimentally prove the superiority of the proposed indices over the known ones. This is confirmed by the value of standard deviation which is minimal in the proposed indices of interaction quality  $(I_{QI1}), (I_{QI2}), (I_{QI3}), (I_{QI4})$  in contrast to the known ones. Thus, the software implementation of the index assessment technology was tested.

**6. Discussion of the results obtained in the study of the index assessment technology**

The experimental results obtained in the study of the index of interaction quality (Table 13) indicate a significant improvement of efficiency of quality assessment by means of improving the mathematical apparatus of index determination.

In contrast to the known indices [24], the mathematical apparatus of the proposed indices takes into account single, double and triple interaction of integrated indicators  $(I_{QI1})$  and the synergistic effect  $(I_{QI2}), (I_{QI3}), (I_{QI4})$ . The study featured the use of four indices describing the quality of interaction of subsystem elements. Two indices describe the quality of interaction of three subsystem elements (social, technical, and informational). The next two indices define the quality of interaction of four or more subsystems (taking into account the safety and motivation subsystems).

Due to the use of combinatorics elements, the indices  $(I_{QI2}), (I_{QI3}), (I_{QI4})$  have a different maximum number

of theoretical combinations of estimate series: 125, 625 and 3125. In addition, an increase in the number of subsystems complicates the procedure of determining the weight coefficients.

In the process of checking the adequacy of the proposed indices on the basis of theoretical estimates, the existence of insignificant deviations of estimates from the study scope was established. This is especially true for the models that describe four or more subsystem elements. Therefore, when examining experimentally these indices, one should be more careful in determining the proportion of weights that provide flexibility of formulas.

Due to taking into account the synergetic effect, an advantage over existing approaches was revealed when determining the quality of interaction of subsystem elements. The decrease in the mean-square deviation compared to the existing data is a sign of index efficiency. Due to this, there were almost no permanent deviations during the experiments.

A software implemented technology of index assessment was offered. In contrast to the previous study stage [22, 23], the improved technology of index assessment was offered. It enables obtaining of four separate estimates of indices of interaction quality.

The use of the proposed approach only for operators of machining centers or NC machine tools using a five-point scale is a limitation of this study.

Insufficient perfection in determining the weight coefficients is a disadvantage of this study. In the future, the determination of weight coefficients can be eliminated by eliminating the subjective factor of personality.

Further study development involves the use of index estimates for decision-making on recruitment, solving the classification problems and forecasting.

## 7. Conclusions

1. The problem of improving the method of index assessment was solved by mathematical analysis of variables taking into account single, pairwise and triple interaction of integrated indicators and synergetic effect for the first ( $I_{Q1}$ ) and other ( $I_{Q2}$ ), ( $I_{Q3}$ ), ( $I_{Q4}$ ) indices, respectively.

2. The problem of proving the adequacy of the proposed indices was solved by establishing the equality of group averages by the method of single-factor variance analysis with a confidence level  $\alpha=0.95$  where the similarity of group averages was established. According to the Kolmogorov-Smirnov criterion, normality of distribution was established where  $\alpha$  was more than 0.2.

3. The issue of determining the advantage of the proposed technology over existing ones was solved for a theoretical sample based on mean-square deviation. This was achieved by comparing the values of mean-square deviation  $S(I)=0.85$  for the known index and  $S(I_{Q1})=0.82$ ;  $S(I_{Q2})=0.073$  for the proposed indices of quality of the relationship of three subsystems. Besides, compare  $S(I)=0.849$ ;  $S(I)=0.633$  for the known indices and  $S(I_{Q3})=0.695$ ;  $S(I_{Q4})=0.618$  for the proposed indices of relationship quality with four and five subsystem elements, respectively.

4. The proposed technology of index assessment differs from the existing ones by using improved indices as the method of assessing the quality of interaction of subsystem elements.

5. The proposed technology was experimentally verified by comparing the values of the standard deviation of the known indices  $S(I)=0.947$ ;  $S(I)=0.833$ ;  $S(I)=0.594$  with the proposed ones:  $S(I_{Q1})=0.812$ ;  $S(I_{Q2})=0.271$ ;  $S(I_{Q3})=0.675$ ;  $S(I_{Q4})=0.57$ , respectively. This verification confirms the effectiveness of the proposed software which implements the technology of index assessment.

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