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*Запропоновані методи вираховування індексних оцінок при відборі верстатників забезпечують більшу точність, чим відбір на основі експертних оцінок та їх інтегрованих показників груп експертних оцінок.*

*Індексні оцінки вираховуються на основі алгоритму об'єднання самооцінок і експертних оцінок у Індекс якості сформованості професійної компетентності верстатника (ІПК), а об'єднання експертних оцінок і нормованих оцінок – у Індекс якості підготовки верстатника (ІЯП). Запропоновані методи вираховування індексних оцінок комплексно характеризують елемент функціонування соціальної підсистеми системи «Верстатник – Верстат з числовим програмним керуванням – Керуюча програма виготовлення деталі», ВВКП.*

*Індексні оцінки характеризують міру узгодженості/розбалансованості самооцінок і експертних оцінок та експертних оцінок і нормованих оцінок, а також системних взаємозв'язків верстатника з елементами соціальної, технічної та інформаційної підсистем відкритої системи.*

*Переваги відбору верстатників на основі індексних оцінок, у порівнянні з експертними оцінками, спостерігалися при співставленні двох рядів рангових місць у списку прізвищ. Ряди рангових місць отримані з використанням методів – лінійної згортки, мультиплікативної згортки. Доведено, що відбір верстатників з використанням методу лінійної згортки значно точніший, якщо проводиться на основі індексних оцінок, при порівнянні з експертними оцінками. Для відбору верстатників згідно вимог Замовника доцільно використовувати метод бінарного пошуку*

*Ключові слова: самооцінки, експертні оцінки, нормовані оцінки, об'єктивні оцінки, індексні оцінки*

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# APPLICATION OF INDEX ESTIMATES FOR IMPROVING ACCURACY DURING SELECTION OF MACHINE OPERATORS

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## 1. Introduction

Self-assessments estimate personality characteristics while expert estimates describe products from machine operators' activities. Therefore, the selection of machine operators that act as elements of complex systems is successfully carried out using expert estimates.

A method of fuzzy logic proposed in paper [1] for the selection of professionals based on expert estimates makes it possible to obtain stable ranked lists of surnames that are consistently repeated. The selection of machine operators based on expert estimates only has its limitations. Specifically, it does not make it possible to use for its analysis the indicators defining the degree of consistency between expert

estimates and his/her self-assessment, compliance of achievements to the sectoral regulatory standard.

A more accurate selection of machine operators that applies mathematical methods is carried out by combining expert estimates and self-assessment and the sectoral regulatory standard requirements, whose series are derived from the application of a unified list of indicators and a similar serial scale.

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## 2. Literature review and problem statement

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The known methods for acquiring primary empirical assessments, their processing, as well as the construction of a database, define the substantive basis of mathematical methods for the selection of professionals. Studies into effectiveness of the selection of professionals that act as elements of open systems employ methods for obtaining expert estimates, which do not imply the participation of a large group of experts.

A study into the selection of program groups [2] makes it possible to obtain the lists of models for ranking and performance assessment. The proposed method has its advantages, but it was almost never applied for the selection of machine operators.

Paper [3] suggested using the known modified selection method electra III that makes it possible to obtain a ranked list of alternatives (selection options) applying a fuzzy model. The value of this method is in the implementation of high-quality and precise selection based on expert estimates.

A study of the interaction between an expert system and the system of intelligent analysis [4] reported the increased possibilities of the expert system and improvement in the accuracy of object selection. The selection was based on expert assessments, and, in fact, did not apply mathematical methods for obtaining index estimates.

In order to receive recommendations about the proper choice of a specialist [5], experts employed methods of feature selection. Based on the results from this study, the accuracy of selection improves by ninety percent. However, the proposed technology based on the method of feature selection was not studied using index estimates. Therefore, to improve the quality and accuracy in the selection of professionals based on expert assessments, it is necessary to employ their self-assessment and the standard normalized estimates. Unification of the three indicated groups into integrated indicators (numeric indices) would make it possible to take into consideration, when selecting machine operators, the degree of coherence/imbalance in the dependences that link them.

Experimental works [6, 7] studied the methods for combining expert estimates into a rating integrated indicator [6] and the indicator «competence in the field of networked information technologies» [7]. Computation of integrated assessments made it possible to improve accuracy in the selection of professionals using the methods of analysis of hierarchies and ranking.

The selection of objects as the elements of open systems implies the application of various groups of estimates for a specialist [8, 9]. In social subsystems, the selection of professionals is carried out based on how a specialist self-assesses intelligence and own capability to learn, supplemented by expert estimates. A given approach makes it possible to perform a comparative analysis of effectiveness estimates in the selection of machine operators who have the highest scores.

A study into the selection of professionals [10] is based on the use of a hierarchy analysis method, which implies the

application of estimates by one or more experts. This method was combined with factorial and clustered analyses based on expert estimates, which made it possible to ensure the required selection accuracy.

An analysis of available studies reveals that the selection of machine operators involving index estimates was not investigated enough; its accuracy was not examined. The selection of machine operators based on index estimates implies additional criteria for selection accuracy. Such criteria are the measure of interconnectedness among various groups of estimates, which manifests itself in the interaction between the elements of an open system. Thus, in order to combine expert estimations, self-assessments, as well as other estimates, of the social maturity of pupils' personality, paper [11] devised a known formula for the index of development of an integrated personality. The formula for the index of development of an integrated personality is used to compute the index estimates, which underlies the successful selection of machine operators.

To select machine operators based on index estimates, paper [12] applied a unified algorithm for the computation of numeric values for the quality index of professional competence and the quality index of machine operators training [12]. The specified indices are the criteria for improving accuracy of their selection.

Paper [13] applied a formula for the computation of index estimates for the quality of interaction among elements of the social, technical, and informational subsystems within an open complex system that acts as the criterion for its functioning.

Thus, the generalization of constituents from tasks [2–13] shows that the unresolved problem of our time is the selection of machine operators based on index estimates.

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## 3. The aim and objectives of the study

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The aim of this study is to construct new methods for the computation of index estimates by combining self-assessments and expert estimates, as well as expert estimates and the standard normalized estimates, for improving accuracy in the selection of machine operators.

To accomplish the aim, the following tasks have been set:

- to define a unified list of indicators for professional competence of the machine operator and an evaluation scale to obtain the series of primary self-assessments, expert estimates, and the corresponding normalized estimates;
- to build new mathematical methods for the computation of index estimates for two numerical indices;
- to substantiate the appropriateness of using index estimates and respective statistical methods to improve accuracy in the selection of machine operators according to a customer's requirements.

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## 4. The base of index estimates to study improvement in the accuracy of machine operator selection

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The selection of machine operators for manufacturing parts on a CNC machine, in line with a customer's requirements, was performed based on the compiled experimental base sample of 51 machine operators, qualification grade 3, 4, 5, according to the model of General totality from 419 OMMP systems at machine-building plants in the cities of Karlivka, Poltava,

and Kharkiv (Ukraine). Comparative analysis included empirical evaluation of the qualification grade 4 machine operators.

The system OMMP consists of three elements of its subsystems. The social subsystem is described by the estimated quality of formation of professional competence of machine operators and the quality of training a machine operator. The technical subsystem is characterized by the estimated performance of the CNC type machine that is operated by a machine operator. The informational subsystem is evaluated by the complexity level of the software that controls the manufacture of parts on a CNC machine operated by a machine operator. Evaluation of the database Operation of the OMMP system's elements is characterized by two groups of estimates – primary empirical self-assessment, expert estimates, the normalized estimates of industry standard, as well as the index estimates derived on their basis.

## 5. Methods for creating a unified list of indicators and for computing index estimates

### 5.1. Indicators for professional competence of a machine operator as an element of the social subsystem of the OMMP system

Primary empirical estimates for a machine operator are received using a unified list of indicators for the professional competence of the individual, which are divided into three components based on their content (gnostic, motivational, value-productive).

#### Gnostic component

1 – Using a set of different tools for machining parts on a CNC machine (0.176).

2 – Selecting the part machining modes at the control panel of various CNC machines (0.165).

3 – Starting and machining parts of various type of complexity on a CNC machine (0.173).

4 – Shaft alignment using precise-measurement tools for machining parts on a CNC machine (0.17).

5 – Ensuring different classes of part precision machining on a CNC machine (0.163).

6 – Programming a control panel on a CNC machine with a single spindle and a varying number of axes (0.151).

#### Motivational component

7 – Improving the sensory-motor reaction to accelerate operations on adjusting the part's «zero» to the X axis (0.17).

8 – Compliance with the regulatory requirements for accuracy of part machining on a CNC machine (0.166).

9 – Concentration on standard schemes for the motion trajectory of the cutter during machining a part on a CNC machine (0.171).

10 – Programming the machining of volumetric parts on machine tools with different coordinates (0.156).

11 – Practice of using tools that are fixed in the revolver head (0.177).

12 – Using different systems to transmit signals on part machining quality (wire, optical, and radio channel) during operation of a CNC machine tool (0.158).

#### Value-productive component

13 – I am in control of successive stages of part machining at different coordinate machine tools (0.173).

14 – I measure the spatial dimensions of parts with different coordinate axes using the devices of digital indication (0.183).

15 – I program part machining at the control panel of a CNC machine that has one or more spindles (0.159).

16 – I use measuring devices with a high level of precision (0.162).

17 – I set the tool position zero points when setting a machine for operation (0.163).

18 – I use measuring devices of varying complexity (0.158).

Applying a unified list of indicators for professional competence and a similar serial scale makes it possible to obtain the series of primary empirical self-assessments, expert estimates, and normalized ratings. The specified estimates for the mathematical methods of combination underlie the computation of index estimates.

### 5.2. New and modified mathematical methods for computing index estimates

A numeric value for the Quality index of the formed professional competence of a machine operator ( $I_{PC}$ ) is calculated using a mathematical method for combining the self-assessments and expert estimates. The specified index is composed of three numerical coefficients ( $K_G$  – gnostic,  $K_M$  – motivational,  $K_{VP}$  – value-productive). Each coefficient is calculated separately by the method for combining the two series of empirical estimates, self-assessment ( $A^S$ ) –  $x_1, x_2, x_3, \dots, x_6$ ; expert estimate ( $A^e$ ) –  $y_1, y_2, y_3, \dots, y_6$ .

The estimates obtained by using a unified list of indicators are calculated from formula (1), which is a notation of the index by Lebedik [9]:

$$K = 0.5 + \frac{9A^e}{10 + 3\chi^2}, \quad (1)$$

where ( $A^e$ ) is the total indicator of expert assessments of the  $i$ -th number of the corresponding indicator, where:

$$A^e = \sum_{i=1}^n y_i B_i,$$

where  $n$  is the number of indicators;  $B_i$  is the coefficient of specific weight of the  $i$ -th parameter (indicator), and  $\sum_{i=1}^n B_i = 1$ ;  $\chi^2$  is the generalized indicator of the sum of differences between the series of a machine operator's self-assessment ( $x$ ) and expert estimates ( $y$ ), calculated from formula:

$$\chi^2 = \sum_{i=1}^n \frac{(x_i - y_i)^2}{(x_i + y_i)} \cdot B_i.$$

The derived numerical coefficients of gnostic ( $K_G$ ), motivational ( $K_M$ ) and value-productive ( $K_{VP}$ ) components of personality are merged into the numeric Quality index of the formed professional competence of a machine operator ( $I_{PC}$ ) using formula (2):

$$I_{PC} = \sqrt[3]{K_G \cdot K_M \cdot K_{VP}}, \quad (2)$$

where  $K_G, K_M, K_{VP}$  are the coefficients of gnostic, motivational, and value-productive components of a specialist's personality.

The numeric value for the specified index registers the extent of coherence/imbalance in consciousness, which is diagnosed only by a self-assessment method, social and practical activities of the individual, whose products are estimated using expert assessments.

The numeric value for the Quality index of training a machine operator ( $I_{QT}$ ) is calculated using a mathematical method for combining expert estimates and the normalized estimates based on industry standard [14]. The specified index is composed of three numerical coefficients ( $K_G$  – gnostic,  $K_M$  – motivational,  $K_{VP}$  – value-productive).

Each coefficient is calculated separately by the method for combining the two series of empirical estimates, expert estimate ( $A^e$ ) –  $y_1, y_2, y_3, \dots, y_6$ ; evaluation of requirements by industry standard ( $A^{st}$ ), –  $c_1, c_2, c_3, \dots, c_6$ . The estimates obtained using a unified list of indicators and a similar serial assessment scale are calculated from formula (1).

The derived numerical coefficients for the gnostic ( $K_G$ ), motivational ( $K_M$ ) and value-productive ( $K_{VP}$ ) components of personality is merged into the numeric Quality index of training a machine operator ( $I_{QT}$ ) using formula (3):

$$I_{QT} = \sqrt[3]{K_G \cdot K_M \cdot K_{VP}} \tag{3}$$

The numeric value for the Quality index of training a machine operator ( $I_{QT}$ ) registers the degree of compliance between the products produced by him, which are estimated by experts, and the regulatory requirements – estimates for the standard.

A comparative analysis of effectiveness of selection of the qualification grade 4 machine operators based on expert and index estimates employed known methods of linear convolution, analysis of hierarchies, multiplicative convolution. The series of primary empirical expert assessments are given in Table 1. Personal estimates for machine operators were changed in accordance with the Law of Ukraine «On protection of personal data»: «Personal data, except for impersonal data, are the information with restricted access» [15].

Table 1

Expert estimates (EE) for the qualification grade 4 machine operators, derived for 18 indicators for the individual's professional competence

| Ordinal numbers (No. 1–9) of machine operators in the list | Series of expert estimates for machine operators based on 18 indicators for professional competence |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |
|--|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
|  | 1   | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| No. 1  | 4   | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 5 | 3  | 4  | 4  | 3  | 4  | 3  | 4  | 4  | 3  |
| No. 2  | 3   | 3 | 3 | 4 | 3 | 4 | 4 | 3 | 5 | 3  | 4  | 3  | 5  | 3  | 3  | 3  | 3  | 3  |
| No. 3  | 4   | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5  | 3  | 3  | 4  | 5  | 3  | 3  | 3  |    |
| No. 4  | 4   | 4 | 3 | 3 | 3 | 3 | 4 | 3 | 4 | 3  | 3  | 3  | 3  | 3  | 4  | 3  | 3  |    |
| No. 5  | 4   | 2 | 5 | 4 | 4 | 5 | 3 | 4 | 4 | 4  | 5  | 4  | 5  | 5  | 3  | 3  | 4  | 3  |
| No. 6  | 3   | 4 | 3 | 4 | 4 | 3 | 4 | 3 | 4 | 3  | 4  | 4  | 4  | 3  | 3  | 3  | 3  | 3  |
| No. 7  | 4   | 4 | 4 | 4 | 4 | 2 | 4 | 4 | 3 | 3  | 5  | 3  | 1  | 4  | 4  | 3  | 5  | 1  |
| No. 8  | 5   | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4  | 4  | 4  | 4  | 4  | 4  | 4  | 4  | 4  |
| No. 9  | 4   | 4 | 5 | 4 | 4 | 5 | 4 | 4 | 4 | 2  | 5  | 4  | 5  | 5  | 2  | 3  | 4  | 3  |

In addition, the selection of machine operators was carried out by methods of linear convolution, multiplicative convolution, analysis of hierarchies, separately, based on the index estimates whose numerical values are given in Table 2.

Table 2

Empirical numerical values for the index estimates of machine operators that are calculated using methods of the Quality index of the formed professional competence of a machine operator ( $I_{PC}$ ), the Quality index of training a machine operator ( $I_{QT}$ )

| Ordinal numbers of machine operators (No. 1–9) in the list | Empirical numerical values for the index estimates of machine operators (diagnostic sample, 2017) |          |
|--|---|----------|
|  | $I_{PC}$  | $I_{QT}$ |
| No. 1  | 3.8   | 3.84     |
| No. 2  | 3.5   | 3.49     |
| No. 3  | 3.9   | 3.90     |
| No. 4  | 3.5   | 3.49     |
| No. 5  | 3.9   | 3.91     |
| No. 6  | 3.6   | 3.60     |
| No. 7  | 3.6   | 3.59     |
| No. 8  | 4.2   | 4.24     |
| No. 9  | 4.0   | 3.99     |

To study the accuracy and advantages in the selection of machine operators based on expert and index estimates, the results were compared from using linear convolution and a method of multiplicative convolution.

**5. 3. Selection of machine operators using a method of linear convolution**

The method of linear convolution was used to determine the rankings of machine operators, initially based on expert estimations, and then based on the integrated and index estimates, where the weighted sums of estimates for each surname of a machine operator are first calculated by formula (4) from [16]:

$$K_j(\alpha) = \sum_{j=1}^n x_{ij} w_j, \tag{4}$$

where  $x_{ij}$  are the expert estimates (index estimates);  $w_j$  is the specific weight of criteria for expert estimates (criteria for index estimates).

This study employed a comparative analysis of results from the selection of machine operators using a method of linear convolution based on empirical numerical values for assessments by various methods (No. 1–4): expert estimations (No. 1); the integrated indicator of competence in the field of networked information technologies (method No. 2); the quality index of the formed professional competence (method No. 3); the quality index of training (No. 4), which are given in the summary Table 3.

It was established that based on the results from the selection of machine operators using a method of linear convolution based on estimates that are calculated by different methods: No. 1 (expert estimates) and No. 2 (the integrated indicator for a group of expert estimates), the machine operator No. 8 demonstrates the highest aggregate score:

$$\sum_{j=1}^n x_{ij} = 4.16 \text{ and } \sum_{j=1}^n x_{ij} = 0.0015.$$

**Table 3**  
Results of selecting machine operators by the method of linear convolution based on estimates that are calculated by different methods: No. 1–4

| Ranking | Ranking of machine operators and methods (No. 1–4) for the computation of their estimates |                                   |  |                                   |  |                                   |  |                                   |
|---------|---|-----------------------------------|--|-----------------------------------|--|-----------------------------------|--|-----------------------------------|
|         | Ordinal number of machine operator in the list  | Estimate calculation method No. 1 | Ordinal number of machine operator in the list | Estimate calculation method No. 2 | Ordinal number of machine operator in the list | Estimate calculation method No. 3 | Ordinal number of machine operator in the list | Estimate calculation method No. 4 |
| 1       | No. 8   | 4.16                              | No. 8  | 0.0015                            | No. 4  | 15.83                             | No. 4  | 16.0                              |
| 2       | No. 5   | 3.94                              | No. 3  | 0.0014                            | No. 2  | 15.08                             | No. 2  | 15.0                              |
| 3       | No. 9   | 3.93                              | No. 5  | 0.0014                            | No. 3  | 14.71                             | No. 1  | 14.7                              |
| 4       | No. 3   | 3.85                              | No. 9  | 0.0014                            | No. 1  | 14.70                             | No. 3  | 14.7                              |
| 5       | No. 1   | 3.66                              | No. 1  | 0.0013                            | No. 9  | 14.32                             | No. 9  | 14.5                              |
| 6       | No. 2   | 3.44                              | No. 2  | 0.0012                            | No. 6  | 13.57                             | No. 6  | 13.6                              |
| 7       | No. 6   | 3.44                              | No. 4  | 0.0012                            | No. 7  | 13.57                             | No. 7  | 13.5                              |
| 8       | No. 7   | 3.44                              | No. 6  | 0.0012                            | No. 5  | 13.19                             | No. 5  | 13.1                              |
| 9       | No. 4   | 3.26                              | No. 7  | 0.0010                            | No. 8  | 13.19                             | No. 8  | 13.1                              |

When selecting machine operators based on index estimates (index estimate calculation methods No. 3, No. 4), the machine operator No. 4 ranks first:

$$\sum_{j=1}^n x_{ij} = 15.83 \text{ and } \sum_{j=1}^n x_{ij} = 16.$$

To perform a comparative analysis of stability in the rank series of machine operators that are calculated based on the expert, integrated, and index estimates, using the method of linear convolution, a method of multiplicative convolution was applied as well.

**5. 4. Using the method of multiplicative convolution for testing the stability of machine operators' rankings**

To test these results, additionally used is another method of multiplicative convolution, which is calculated in line with formula (5) from [16]:

$$K_j(\alpha) = \prod_{j=1}^n (x_{ij})^{w_j}, \tag{5}$$

where  $x_{ij}$  are the expert estimates (index estimates);  $w_j$  is the specific weight of criteria in expert estimates (criteria for index estimates).

Results from such calculations are given in Table 4.

The determined score of each machine operator using the method of convolution multiplicative indicates that the selection of machine operators that applies the index estimates demonstrates the indices of greater accuracy.

When using two methods – a linear convolution and a multiplicative convolution method – there is a complete match between the machine operators' rankings.

To check the stability of machine operators' rankings that were obtained using a method of multiplicative convo-

lution, the method of analysis of hierarchies was applied. A given method implies the computation of a geometric mean [17], the sum of specific weight [17], the specific weight of estimates [17], the sum of columns in the matrix of pairwise comparisons [17], the additional quantity [17]. Next, one adjusts the ranking series that are derived separately using expert and index estimates where the index of coherence must be within: «...the range of values 0.1–0.3» [17]. The method of analysis of hierarchies fully confirmed the order of rank estimates for machine operators that were derived previously by other methods where computation was carried out separately based on the expert, integrated, and index estimates.

**Table 4**  
Results from selecting machine operators by the method of multiplicative convolution based on assessments that are calculated by different methods: No. 1–4

| Ranking | Ranking of machine operators and methods (No. 1–4) for computing their estimates |                                   |  |                                   |  |                                   |  |                                   |
|---------|--|-----------------------------------|--|-----------------------------------|--|-----------------------------------|--|-----------------------------------|
|         | Ordinal number of machine operator in the list                                   | Estimate calculation method No. 1 | Ordinal number of machine operator in the list | Estimate calculation method No. 2 | Ordinal number of machine operator in the list | Estimate calculation method No. 3 | Ordinal number of machine operator in the list | Estimate calculation method No. 4 |
| 1       | No. 8  | 4.14                              | No. 8  | 0.8910                            | No. 4  | 223.69                            | No. 4  | 235.2                             |
| 2       | No. 5  | 3.83                              | No. 5  | 0.8901                            | No. 2  | 186.11                            | No. 2  | 186.9                             |
| 3       | No. 3  | 3.81                              | No. 9  | 0.8901                            | No. 3  | 169.17                            | No. 1  | 173.1                             |
| 4       | No. 9  | 3.80                              | No. 3  | 0.8894                            | No. 1  | 169.17                            | No. 3  | 171.4                             |
| 5       | No. 1  | 3.61                              | No. 1  | 0.8877                            | No. 9  | 153.39                            | No. 9  | 161.7                             |
| 6       | No. 6  | 3.41                              | No. 2  | 0.8858                            | No. 6  | 125.10                            | No. 6  | 126.7                             |
| 7       | No. 2  | 3.38                              | No. 6  | 0.8858                            | No. 7  | 125.10                            | No. 7  | 125.3                             |
| 8       | No. 4  | 3.23                              | No. 7  | 0.8858                            | No. 5  | 112.51                            | No. 5  | 112.6                             |
| 9       | No. 7  | 3.16                              | No. 4  | 0.8841                            | No. 8  | 112.50                            | No. 8  | 112.6                             |

The similarity of rank series based on expert assessments was observed by other researchers who have used known methods: «Comparing the results from calculations based on the methods of pairwise comparison and by T. Saaty indicates the validity of the method of paired comparisons» [18]. By using the method of pairwise comparison: «...the matrix is populated with elements in the following way:

$$\alpha_{ij} = \begin{cases} 2, & j (i > j); \\ 1, & (i = j); \\ 0, & i (j > i). \end{cases}$$

The sum  $\sum_{j=1}^n \alpha_{ij}$  makes it possible to estimate the relative significance of objects. The object for which the sum is the largest can be recognized as the most significant» [18].

To run a comparative analysis of accuracy in the selection of the best machine operators by different methods, I shall use the formula of the total magnitude of variability in estimates.

**5. 5. Using a formula of the total magnitude of variability in estimates to determine the accuracy of selection**

To prove the advantage of using index estimates when selecting machine operators at machine-building enterprises, the total magnitude of variability (*R*) was derived, separately, based on the expert estimates, the integrated indicators, index estimates in line with formula (6) from [17]:

$$R = \sum_{i=1}^M R_i, \tag{6}$$

where *M* is the set of criteria; *R<sub>i</sub>* are the magnitudes of variability for each criterion.

The magnitudes of variability in the estimates of machine operators for each selection criterion are given in Table 5.

Table 5

Results of computing the variability in estimates to determine accuracy when selecting machine operators based on the expert, integrated, and index estimates

| Indicators for the method of variability in estimates ( <i>R<sub>i</sub></i> ) when selecting machine operators based on the expert, integrated, and two index estimates |  |   |   |
|--|--|---|---|
| Expert estimates   | Integrated indicator for a group of expert estimations | Quality index of the formed professional competence ( <i>I<sub>PC</sub></i> ) | Quality index of training ( <i>I<sub>QT</sub></i> ) |
| 0.16   | 0.068  | 0.057   | 0.054   |

Using the formula for computing the total magnitude of variability in estimates in order to prove accuracy in the selection of machine operators has made it possible to establish that the total magnitude of variability in the index estimates is significantly lower compared to the expert and integrated assessments.

The results obtained prove the benefit of using mathematical methods in order to compute index estimates and their criteria for improving accuracy in the selection of machine operators. This research has shown that it would suffice, when selecting machine operators for machine-building enterprises with a large database (over 300 machine operators), to use a single method – linear convolution.

Based on the results from selecting a group of machine operators using the index estimates, their list is given in Table 6.

Table 6

Results from selecting the qualification grade 4 machine operators (*n=9*) based on the index estimates, which are calculated using methods for the Quality index of the formed professional competence of a machine operator (*I<sub>PC</sub>*), the Quality index of training a machine operators (*I<sub>QT</sub>*)

| Ranking | Ordinal numbers (No. 1–9) of machine operators in the list | Enterprise                     | <i>I<sub>PC</sub></i> | <i>I<sub>QT</sub></i> |
|---------|--|--------------------------------|-----------------------|-----------------------|
| 1       | No. 9  | Kharkiv Machine-Building Plant | 4.0                   | 3.99                  |
| 2       | No. 5  | Poltava Machine-Building Plant | 3.9                   | 3.91                  |
| 3       | No. 3  | Kharkiv Machine-Building Plant | 3.9                   | 3.90                  |
| 4       | No. 8  | Poltava Machine-Building Plant | 4.2                   | 4.24                  |

When selecting the best machine operators for a Customer, there are discussions about the appropriateness of using the specified methods and certain conflicting contradictions. To resolve them, a qualification board should apply the method for computing a minimum in the variance of functionality to be estimated, which: «...characterizes the spread of elements within a given series in terms of its average value; the lower the variance magnitude, the lower the probability that small elements are present in the series as a solution» [20]. The best machine operator always has the lowest value of variance, which is clearly observed when analyzing the estimates of candidates that take the first four ratings.

**5. 6. The algorithm for using a method of binary search and rapid sorting to select machine operators**

The methods of binary search and rapid sorting in order to analyze quality in the selection of machine operators according to a Customer’s requirements are used based on the index estimates. Index estimates are calculated by methods for combining the self-assessments, estimates of experts, as well as the normalized estimates, obtained by using the uniform list of indicators and a similar serial assessment scale proposed in this paper.

To select machine operators according to the estimates-requirements by a Customer, which are compared against the numerical values for the Index estimates of machine operators, included in a database, one first sorts them using a method of rapid sorting: «The array will be divided as follows: *R<sub>1</sub>, R<sub>2</sub>, ..., R<sub>i-1</sub>, R<sub>i</sub>, R<sub>i+1</sub>, ..., R<sub>m</sub>*, in this case, *R<sub>1</sub> < X, I, ..., i-1; R<sub>m</sub> <= X, m=i-1, ..., n*. The left-hand side of the array will contain all elements that are smaller than the base one, while the right-hand side will include those that are larger, as well as the base element itself. Next, this method will be applied recursively to each of these subsets. The recursion ends when all subsets are composed of a single element or the entire array is ordered» [21]. The method of rapid sorting indicates the construction of an appropriate algorithm for searching for machine operators.

The requirements to the preparedness of selected machine operators that would manufacture specified parts are defined by a Customer in the Form of the customer’s estimates-requirements «Fabrication of a component on a CNC machine» (Table 7).

The algorithm for a binary search was built using well-known basics: «...Algorithm D is recorded by the following sequence of steps:

- The sorted vector key (*i, j*) is sent to the input
- D0. Initialize the indices *i, j*.
- D1. Repeat steps D2–D5, until *i < j*.
- D2. Computation of the tree root’s index: *m = [(i + j) / 2]*.
- D3. If [key (*m*)] = *K*, then REZ = *m*, proceed to step D6.
- D4. Otherwise: If [key (*m*)] < *K*, then *i = m + 1* (search to the right); proceed to D2.
- D5. Otherwise *j = m - 1* (search to the left); proceed to D2.
- D6. Exit» [21, 22].

Quality of the selected machine operators is determined by comparing the actual estimates, entered to the database, and the estimates, specified by the Customer in the Form «Fabrication of a component on a CNC machine».

If the Customer requires that the order should be performed only by those machine operators whose performance is assessed, based on all six requirements, at the level of a «very high score», then this requirement is registered in line with a scale by number 5.

**Table 7**  
**Form of the customer’s estimates-requirements «Fabrication of a component on a CNC machine»**

| No. of entry | Parameters to evaluate elements in the OMMP system  | Sequential 5-point scale  | Customer’s estimates-requirements |
|--------------|---|---|-----------------------------------|
| 1            | Complexity level of software for a component manufacturing on a CNC machine (informational subsystem) | 1 – Shaft   | 1                                 |
|              |   | 2 – Lever   | 2                                 |
|              |   | 3 – Casing  | 3                                 |
|              |   | 4 – Gear box  | 4                                 |
|              |   | 5 – Using manipulating robots                                     | 5                                 |
| 2            | Type of CNC machine performance operated by machine operator (technical subsystem)                    | 1 – (N – normal precision)  | 1                                 |
|              |   | 2 – (E – Enhanced precision)                                      | 2                                 |
|              |   | 3 – (H – High precision)  | 3                                 |
|              |   | 4 – (A – particularly high precision), (C – particular precision) | 4                                 |
|              |   | 5 – Using manipulating robots                                     | 5                                 |
| 3            | Qualification grade of machine operator to operate a CNC machine (social subsystem)                   | Machine operator qualification grade without CNC                  | 1                                 |
|              |   | Qualification grade 2 to operate a machine without CNC            | 2                                 |
|              |   | Qualification grade 3   | 3                                 |
|              |   | Qualification grade 4   | 4                                 |
|              |   | Qualification grade 5   | 5                                 |
| 4            | Quality index of the formed professional competence of a machine operator (social subsystem)          | 1 – (to 1.0 – starting)   | 1                                 |
|              |   | 2 – (above 1.0–2.0 – minimal)                                     | 2                                 |
|              |   | 3 – (above 2.01–3.0 – basic)                                      | 3                                 |
|              |   | 4 – (above 3.01–4.0 – sufficient)                                 | 4                                 |
|              |   | 5 – (above 4.01–5.00 – high )                                     | 5                                 |
| 5            | Quality index of training a machine operator (social subsystem)                                       | 1 – (to 1.0 – starting)   | 1                                 |
|              |   | 2 – (above 1.0–2.0 – minimal)                                     | 2                                 |
|              |   | 3 – (above 2.01–3.0 – basic)                                      | 3                                 |
|              |   | 4 – (above 3.01–4.0 – sufficient)                                 | 4                                 |
|              |   | 5 – (above 4.01–5.00 – high )                                     | 5                                 |

The Customer can reduce the requirements to machine operators to the level of a «high score», it is registered in a scale by number 4.

In practice, the Customer often gives differentiated estimates in the Form of estimates-requirements «Fabrication of a component on a CNC machine» for all six parameters.

*The algorithm for using a method of binary search and rapid sorting to select machine operators according to a Customer’s requirements (stepped search activities – from 1 to 13).*

*Step 1.* Generate the list of machine operators whose estimate of the type of a CNC machine tool performance ( $O_{Ti}$ ) matches that of the Customer.

*Step 2.* Check the list of machine operators, a sample of whom remained after stage 1 of the selection process, whose estimates in block 2 coincide with the requirements of the Customer.

*Step 3.* Generate the list of machine operators whose estimate of the complexity level of the software that controls

a component manufacture on a CNC machine ( $O_{Li}$ ) matches the assessment by the Customer.

*Step 4.* Check the list of machine operators, a sample of whom remained after selection stages 1 and 2, whose estimates in block 4 coincide with the requirements by the Customer.

*Step 5.* Generate the list of machine operators whose estimates of the qualification grade ( $O_{Qi}$ ) matches the estimate by the Customer.

*Step 6.* Check the list of machine operators, a sample of whom remained after selection stages 1, 2, 3, whose estimates in block 6 coincide with the requirements by the Customer.

*Step 7.* Generation of machine operators using an interval estimation of the actual numeric value for Quality index of the formed professional competence of a machine operator of a CNC machine ( $I_{PC}$ ), which integrates by a mathematical method the self-assessment and expert estimates.

*Step 8.* Check the list of machine operators, a sample of whom remained after selection stages 1, 2, 3, 4, whose estimates in block 8 coincide with the requirements by the Customer.

*Step 9.* Generation of machine operators using an interval estimation of the actual numeric value for the Quality index of training a machine operator ( $I_{QR}$ ).

*Step 10.* Check the list of machine operators, a sample of whom remained after stages 1, 2, 3, 4, and 5 of the selection process, whose estimates in block 10 coincide with the requirements by the Customer.

*Step 11.* The surnames of machine operators selected for the task by the Customer for manufacturing a component on a CNC machine are submitted, out of those selected based on the index estimates using the method of linear convolution.

This research has established that the professional quality of selected machine operators does not match a Customer’s requirements when he requires that their performance should be evaluated at the level of a «very high score» for all six requirements, which is registered in a scale by number 5.

However, when the customer reduces the level of requirements to the level of a «high score», which is registered in a scale by number 4, all the selected machine operators (No. 9, No. 5, No. 3, No. 8) meet his requirements in terms of the quality of manufacturing a component on a CNC machine.

The proposed algorithm makes it possible to ensure a quality selection of machine operators for the manufacture of a component according to a Customer’s requirements.

**6. Discussion of results of studying the methods for improving accuracy in the selection of machine operators**

Organization of the selection of machine operators based on the index estimates is continuation of research [6, 7, 11].

The improved accuracy in the selection of machine operators based on methods for computing index estimates is ensured by additional interrelations among self-assessments, expert estimates, and the normalized estimates-requirements. An important indicator of adequate behavior of a machine operator is the consistency/disbalance of estimations by experts and self-assessments. Success of the machine operator is characterized by the measure of targeted approximation of expert assessments of achievements to the normalized estimates-requirements by industry standard in terms of his preparation. The interaction between a machine operator and the elements of both the social and the technical and informational subsystems of the OMMP system is an indicator of the improved quality of production process.

It was also established that accuracy in the selection of machine operators for the manufacture of parts on a CNC machine, whose number in a database exceeds 300 people, is provided by the use of a linear convolution method.

When selecting machine operators by using the index estimates, their advantages over the integrated indicators and expert estimates are clearly registered by the method of variability in estimates. A more accurate selection of machine operators is based on the index estimates.

The smaller indicator for the method of variability in index estimates compared to the estimates by experts and the integrated indicators is explained by the use of functional dependences of self-assessments and expert estimates, as well as expert estimates and the normalized estimates from an industry standard.

The proposed algorithm for the selection of machine operators implies studying those machine operators that operate CNC machines. In order to examine the selection of machine operators that operate machines without CNC, it would suffice to refine the content of separate indicators.

In this study, permanent experts for machine operators were heads of departments. Increasing the number of experts would enhance the accuracy of the selection.

In further studies, it is necessary to examine the impact of forming methods for certification on the accuracy of selecting machine operators based on the index estimates.

index estimates for a more accurate selection of machine operators.

To prove the accuracy of selection, the advantages of index estimates above expert and integrated indicators for a group of expert estimations, a formula for computing the total variability indicator was applied.

The indicator for variability in the two proposed mathematical methods for computing index estimates is  $R_i=0.054$  and  $R_i=0.057$ , respectively.

Known mathematical methods for computing the expert and integrated estimates produce larger variation indicators,  $R_i=0.16$  and  $R_i=0.07$ .

Therefore, the results obtained in the selection of machine operators when using different mathematical methods based on index estimates are more precise compared with the mathematical methods for computing expert estimates and the mathematical methods for computing the integrated indicators for a group of expert estimates.

2. The use of index methods makes it possible to additionally register the measure of coherence/imbalance between self-assessments and expert estimates, expert estimates and the normalized assessments, the systemic interrelations among elements of the social, technical, and informational subsystems within an open system. In contrast to known integrated indicators, the index estimates combine the series of self-assessments and expert estimates, as well as expert estimates and the normalized standard estimation.

3. In order to accurately select machine operators, it would suffice to use a mathematical method of linear convolution, which, based on index estimates, ensures a more accurate selection of machine operators than that based on expert and integrated indicators for a group of expert estimates.

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## 7. Conclusions

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1. The results from this research have made it possible to construct and test mathematical methods for computing

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*Досліджено взаємодію паперів та плівок з тестовою рідиною. Проведено вимірювання крайового кута змочування залежно від виду субстрату та його морфології. Визначено лінійні розміри паперу при зволоженні зразків дистильованою водою, а також досліджено динаміку проникнення води в структуру паперу. Виконано контроль якості всотування рідини паперами. Дослідження позначених показників є необхідним при створенні принципово нових матеріалів для друку. Такі вимірювання дозволяють визначити можливість використання існуючих матеріалів в конкретному технологічному процесі виготовлення поліграфічної продукції.*

*Встановлено взаємозв'язок між ступенем зволоження задрюкованого матеріалу та його друкарсько-технічними властивостями. Зпрогнозовано взаємодію системи «задрюковуваний матеріал – рідина». Визначено вплив пар компонентів на друкарські процеси. Досліджено придатність матеріалів до задрюкування струминним способом і можливість їх використання в плоскому офсетному друці зі зволоженням друкарських форм. При цьому враховувалася можливість забезпечення нормованих значень кольірних характеристик відбитків.*

*Проведена перевірка висунутих гіпотез на відповідність математико-статистичним твердженням достовірності. Проведено розрахунок величин кореляції і встановлення кореляційних зв'язків. Математично доведено, що найбільший опір проникненню води залежить від показника пористості і поверхневого об'єму води. А також значно сильніше залежить від змочування поверхні паперу, ніж від вимірюваного поверхневого об'єму води. Тобто при виборі задрюковуваних матеріалів, потрібно обов'язково враховувати пористість субстрату, ступінь його змочування рідиною. Дані, отримані шляхом вимірювання таких показників, дозволяють прийняти рішення про можливість задрюкування матеріалу різними способами. Результати дослідження дозволяють забезпечити стабільність технологічного процесу і отримання репродукцій з нормованими показниками оптичної густини і кольірними відмінностями не більше 5 одиниць*

*Ключові слова: задрюковуваний матеріал, поліграфічна продукція, струминний друк, крайовий кут, змочування поверхні*

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## RESEARCHING THE INTERACTION OF DIFFERENT PRINTED MATERIALS TYPES WITH LIQUIDS

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### 1. Introduction

The interaction of the printed surface with the liquids is a must in many technological processes of printing. Here

are the cases: applying the dampening solution, printing with the ink-water emulsion in offset printing [1], using the inks in inkjet printing [2], water-soluble inks in the flexographic printing, etc. Selection of the technological process