Models and algorithm for managing of the human capital development in a digital transformation of the machine-building enterprise

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Abstract. The article is devoted to the development of models and an algorithm for managing the process of continuous training of personnel as the most important direction in the development of human capital of an engineering enterprise. The proposed approach is based on a competency-based approach to learning. The paper proposes an algorithm for managing staff training. The basis of the algorithm is made up of mathematical models: a two-criteria model for the formation of an effective test package and a model for the formation of an optimal staff training schedule. The model for the formation of an effective test package makes it possible to select the minimum set from the set of tests, which makes it possible to obtain a quantitative assessment of the employee's competency level. The model for creating the optimal schedule for staff training allows each employee to choose a program and a time period for training that ensure that the company achieves the maximum value of the total competence of employees. The model takes into account the production capabilities and needs of the enterprise in qualified personnel in the context of digital transformation.

1. Introduction
Currently, the introduction of advanced digital technologies is a key factor in ensuring the competitiveness and innovative development of the economy. A special role in the processes of digital transformation belongs to the enterprises of the machine-building complex, which provide technical and technological equipment for the production of the entire economic system [1].

The success and timeliness of innovative transformations in mechanical engineering contributes to an increase in product quality while reducing production costs and opens up new possibilities for the use of manufactured equipment, new effective positions in the machine-building sales markets, and new horizons for international cooperation. At the same time, the digital transformation of machine-building enterprises is impossible without qualified specialists who are able to effectively combine intellectual capital and technological resources to develop and commercialize domestic know-how in the domestic and foreign markets. Thus, the problem of the formation of mechanisms for the
successful development of human capital as a driver of accelerated innovative development of engineering enterprises and the country's economy as a whole is relevant. The theoretical platform for solving the described problem is the concept of the development of human capital, the origin of which researchers refer to the first half of the XX century [2]. The development of the theory of human capital as a key factor in production, understanding of the employee’s value and various aspects of his skills and knowledge is associated with the works of scientists of the Chicago School [3-4]. Modern economic and sociological works prove that for a quality human capital that can support a technological breakthrough, it is necessary to invest in a person, stimulate the growth of human capital, build new technological chains and form appropriate management systems [5]. Practice confirms that the basis of the human capital development system of advanced countries is the progressive technology of continuing education and vocational training and retraining in the workplace [6].

Modern companies and scientists offer a fairly extensive list of diverse methods of professional training and retraining of personnel [7-9]. At the same time, the organization of a continuous educational process and its careful planning is no less important and significant for engineering enterprises. Educational processes as one of the main factors in the development of human capital should be integrated into the main production and management cycles and meet the goals of enterprise development [10, 11].

The aim of this work is to develop models and algorithms that provide mathematical support for managing the processes of training and retraining of personnel at an engineering enterprise as an essential component of the development of human capital. A feature of the study is the competency-based approach to training, which corresponds to modern educational technologies of most of the leading countries of the world, including the Russian Federation. In accordance with this approach, an algorithm is proposed that allows:

- for each employee of a machine-building enterprise, choose a training package that provides an increase in the level of competence;
- create an optimal schedule of staff training, which allows to achieve the maximum competence of employees, taking into account the production capabilities and needs of the enterprise.

2. Description of approach
Consider a unit of an engineering enterprise in which \( N \)-employees work. Employees must be trained during a planned time interval consisting of \( T \) periods (\( t – planning\ period\ period\ number, t = 1, ..., T \)).

We believe that employees can be divided into \( M \) groups according to their functional responsibilities: \( G_1, G_2, ..., G_M \).

The number of each group of employees \( G_m \) is denoted by \( N_m \), where \( m – group\ number \), \( m = 1, ..., M \). Wherein \( N_1 + N_2 + ... + N_M = N \). The serial number of the group employee \( G_m \) is denoted by the index \( i_m \), where \( i_m = 1, ..., N_m, m = 1, ..., M \).

We assume that the same qualification requirements are presented to the employees of each group, and each employee has certain personal abilities to solve a certain range of professional tasks (compe...
business processes; \( C_i \) – average cost of doing business processes; \( D_{i,t} \) – the average planned number of business processes in the period \( t \).

Each training program \( k_m \) provides the employee \( i_m \) with the following changes: \( \Delta R_{i_m}^k \) – change (in shares to the current value) of the competence of the employee; \( \Delta Q_{i_m}^k \) – change in the average quality of business processes; \( \Delta H_{i_m}^k \) – change in the average execution time of business processes; \( \Delta C_{i_m}^k \) – change in the value of business processes.

The management of the enterprise is ready to allocate financial resources in volume \( J \) for staff training with a separation from production. It is required to formulate a mechanism for supporting staff training management, which allows, within the allocated budget and production needs, to form an optimal schedule for staff training.

To solve this problem, an algorithm for supporting staff training management has been developed, consisting of the following main steps:

Stage 1. Formation of groups of employees. Determination of characteristics (competencies) adopted to assess the competence of employees of each group.

Stage 2. Formation of an effective test suite for the quantitative assessment of the competency level of employees of each group.

Stage 3. Organization and conduct of testing employees to determine the level of competence. Processing test results, forming a quantitative assessment of the competency level of each employee.

Stage 4. Formation of training programs for each group of employees. Determining the expected results of employee training for each program.

Stage 5. Formation of an optimal schedule of staff training, which allows to achieve the maximum amount of competency levels of employees taking into account the production capabilities and needs of the enterprise.

Let us dwell in more detail on the issues of mathematical support for the practical implementation of stages 2 and 5.

We will assume that at stage 1, specialists on work with the personnel of the enterprise formed groups of employees and for each group \( m=1,...,M \) the set of competencies (characteristics) that employees of this group should have:

\[
F^m = \{F_1^m, F_2^m, ..., F_{S_m}^m\}, \quad s - \text{competency number}, \quad s = 1, ..., S_m.
\]

Currently, a fairly large number have been developed, many of which evaluate the employee on a cross-cutting set of qualities. Therefore, the main task of this stage of the algorithm is to choose such a minimal set of tests with which it is possible to obtain an assessment of the competence of an employee. We propose its solution using a two-criteria model for the formation of an effective test suite.

We will assume that a list of \( L \) tests is known to evaluate a group of employees \( G_m \), \( l \) – test serial number \( l = 1, ..., L \). Each test may or may not require quality. \( F_s^m (s = 1, ..., S_m) \). We believe that on the basis of the opinion of the company's specialists, a matrix of degrees of test compliance with the qualities of the position of the group employees can be formed \( W = (w_{sl}) \), where \( s = 1, ..., S_m, \quad l = 1, ..., L \). The elements of the matrix \( 0 \leq w_{sl} \leq 1 \) show the extent to which the test with the number \( l \) allows you to evaluate the quality \( F_s^m \).

To formalize the model, we introduce discrete variables:

\[
x_i = \begin{cases} 
1, & \text{if test } l \text{ is included in the package}, \\
0, & \text{otherwise}.
\end{cases}
\]
Then the two-criteria model for the formation of an effective test package can be written as follows:

\[ \begin{align*}
\sum_{i=1}^{L} x_i &\rightarrow \text{min}, \quad \sum_{s=1}^{L} \sum_{l=1}^{S} w_{sl} x_i \rightarrow \text{max}, \\
\sum_{i=1}^{L} a_{sl} \cdot x_i &\geq 1, \quad s = 1, \ldots, S_m,
\end{align*} \] (1)

Constraint (2) means that each competency must be evaluated by at least one test. Moreover, the parameter \( a_{sl} = 1 \), if the test \( l \) evaluates the characteristic \( F_{m}^{s} \) and \( a_{sl} = 0 \) otherwise.

Model (1) - (3) contains two criteria. By the method of weighted sums, it can be reduced to the weighted problem of minimal coverage and solved by the method of branches and boundaries.

The implementation of stage 5 is proposed to be carried out on the basis of a solution to the model for the formation of an optimal staff training schedule. Let's move on to its description.

We introduce model variables:

\[ z_{kt}^{i,m} = \begin{cases} 1, & \text{if a program } k_{m} \text{ is selected for an employee } i_{m} \text{ in a period } t, \\ 0, & \text{otherwise}. \end{cases} \] (4)

As the objective function, we take the sum of employee competency levels:

\[ \sum_{m=1}^{M} \sum_{i_{m}=1}^{N_{m}} \sum_{k_{m}=1}^{K_{m}} t \left[ 1 + \sum_{k_{m}=1}^{K_{m}} \Delta R_{m}^{k_{m}} \sum_{t=1}^{T} z_{kt}^{i,m} \right] \rightarrow \text{max}. \] (5)

Here are the model limitations.

**Limitation 1.** Each employee during the planning period may be offered no more than one training program:

\[ \sum_{k_{m}=1}^{K_{m}} \sum_{t=1}^{T} z_{kt}^{i,m} = 1, \quad i_{m} = 1, \ldots, N_{m}; \quad m = 1, \ldots, M. \] (6)

**Limitation 2.** As a result of mastering training programs, the quality of business processes in each group of employees should not be lower than a certain (planned) level \( \Theta_{m} \):

\[ \sum_{i_{m}=1}^{N_{m}} \frac{Q}{N_{m}} \left[ 1 + \sum_{k_{m}=1}^{K_{m}} \Delta Q_{m}^{k_{m}} \sum_{t=1}^{T} z_{kt}^{i,m} \right] \geq \Theta_{m}, \quad m = 1, \ldots, M. \] (7)

**Limitation 3.** As a result of training, the cost of performing business processes in each group of employees should not exceed a predetermined threshold value \( J_{m} \):

\[ \sum_{i_{m}=1}^{N_{m}} C_{i_{m}} \left[ 1 - \sum_{k_{m}=1}^{K_{m}} \Delta C_{i_{m}}^{k_{m}} \right] \leq J_{m}, \quad m = 1, \ldots, M. \] (8)

**Limitation 4.** As a result of training, the average execution time of business processes in each group of employees should not exceed a predetermined threshold value \( V_{m} \):

\[ \sum_{i_{m}=1}^{N_{m}} H_{i_{m}} \left[ 1 - \sum_{k_{m}=1}^{K_{m}} \Delta H_{i_{m}}^{k_{m}} \right] \leq V_{m}, \quad m = 1, \ldots, M. \] (9)
Limitation 5. During training, the employee ceases to perform duties. The training process should be organized so that no more than 30 percent of the planned time is paid due to overtime work of the remaining employees:

\[
0.7 \cdot \sum_{i_u=1}^{N_u} C_{i_u} \cdot D_{i_u} = \sum_{i_u=1}^{N_u} \left( C_{i_u} \cdot D_{i_u} \left( 1 - \frac{1}{T} \sum_{k_m=1}^{K_m} \sum_{t=1}^{T} (\Delta C_{i_u}^{k_m}) \cdot D_{i_u} \left( 1 - \frac{1}{T} \sum_{k_m=1}^{K_m} \sum_{t=1}^{T} (\Delta C_{i_u}^{k_m}) \right) \right) \right) \leq 0. \tag{10}
\]

Limitation 6. The cost of training employees should not exceed the amount of allocated funds \( J \):

\[
\sum_{m=1}^{M} \sum_{i_u=1}^{N_u} S_{i_u}^m \cdot z_{i_u}^m \leq J, \tag{11}
\]

where \( S_{i_u}^m \) – the cost of training one employee for the program \( k_m \).

The model for creating a staff training schedule (4) - (11) is an integer linear programming problem with Boolean variables \( z_{i_u}^m \in \{0,1\} \). It is proposed to use the branch and bound method as a method for solving the problem.

3. Practical calculations

For practical implementation of the presented approach, a software product developed in the language C#. We present the calculation results for 4 employees of the IT department of a machine-building enterprise. At stage 2 of the algorithm, 3 tests were selected from 34 proposed tests based on model (1) - (3) to assess competency. For training, 4 training programs were offered, the number of training periods \( T=4 \). 1000 monetary units have been allocated for training, the cost of training programs is 290, 220, 250, 300 monetary units, respectively. A fragment of the initial data for one training program is shown in table 1.

| Table 1. Fragment of the initial data. |
|--------------------------------------|
| **Initial data** | **Staff** |
| | 1 | 2 | 3 | 4 |
| Competency level | 70 | 80 | 76 | 72 |
| Change of competence of employees | 0.04 | 0.05 | 0.03 | 0.02 |
| The average level of quality of business processes | 400 | 500 | 300 | 200 |
| Change in the average quality of business processes | 0.05 | 0.05 | 0.04 | 0.03 |

The calculation results showed that employee 1 and employee 3 go through Program 1 in the first period, employee 2 and employee 4 go through Program 2 in the second period and third periods. The maximum amount of competencies of employees amounted to 312.9 units.

4. Conclusion

The approach proposed in this paper to solving the urgent problem of developing mechanisms to support the development of human capital for a machine-building enterprise is based on the use of mathematical tools to make informed decisions in the process of staff training. The paper proposes an algorithm for supporting the management of personnel training, the basis of which are mathematical models. Among these models, a two-criterion model has been formed for the formation of an effective test package, which allows optimizing the testing process for employees and a model for creating an optimal staff training schedule, allowing each employee to choose a program and training period taking into account production capabilities and needs. Practical testing of the proposed approach with the participation of employees of the IT department of a mechanical engineering enterprise, discussion of the results with the management of the enterprise showed the adequacy of the models and the feasibility of their practical use.
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