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Development of a Fuzzy Dynamic Model for the Formation of the Optimal Allocation of Financial Resources for the Maximum Development of Regional Human Capital

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***Abstract*—Currently, human capital is one of the crucial factors in the sustainable development of the region; an increase in the level of human capital is an essential priority that allows to timely achieve the strategic goals of social and economic development. In this study, the issue of the optimal allocation of public financial resources that directly or indirectly affect the development of human capital was addressed. An economic-mathematical model is proposed, the objective function of which is an integrated index that takes into account the degrees of achievement of strategic objectives for the development of human capital. The functional dependencies of human capital performance upon investments are represented by regression equations with lag 2. The model is a fuzzy mathematical programming problem in which the uncertainty and lack of information is modeled using a fuzzy set approach. The transition from a fuzzy optimization problem to a crisp one was performed by setting confidence levels for the objective function and constraints. For several regions of the Russian Federation, the examples of the formation of the optimal structure of public investment, which allows to obtain the maximum progress towards achieving targets in the field of human capital development, were considered over time by years for a given planning period.**

Keywords: human capital, meso-level, investment structure optimization model, economic-mathematical model, fuzzy logic

I. INTRODUCTION

Currently, the transformation of the regional economy is highly dependent on technological and social processes. The high rate and depth of penetration of advanced technologies into the environment of human functioning leads to the emergence of modern innovative enterprises, modification of standard production processes, and change in the usual way of life. For example, the use of robot-aided conveyor lines for assembling car engines leads to increased labor productivity and minimization of defects. The integration of innovative technologies into everyday life necessitates the development of existing human capital to meet the needs of the real sector of the economy. Moreover, the rate of technological modernization requires the implementation of a system of continuous professional training, and, consequently, the creation of the most favorable conditions for the implementation of the training process. The implementation of measures that directly or indirectly affect the development of human capital is possible through the effective investment of public and private financial resources. This, in turn, leads to the relevance of developing methods and models that would allow to evaluate the effectiveness of financial resources allocated for the development of human capital and to formulate recommendations for the investment structure based on this information.

II. METHODS AND LITERATURE

The formation of views on the role and place of investment in human capital was considerably contributed by the fathers of the human capital theory such as T. Schulz, G. Becker, J. Mintzer, and L. Turrow. Their work was continued by modern

scholars who, on the basis of their research, provided recommendations for the development of human capital in enterprises, regions, and countries. Scientific literature allows to distinguish several large groups of studies on this topic.

1. Quantitative assessment of human capital. The most common tool for assessing the human capital of a country or region is the UN method, which is based on the assessment of the human development index [1]. Reference [2] estimates the innovative capital of a region using three groups of indicators: the innovative core of the region, institutional and innovative infrastructure of the region, and innovative capital in research and development. Reference [3] selects 63 indicators for assessing regional human capital that were systematized into seven groups: economic activity, demographic processes, physical health, culture, social health, education, and the attitude of the population to the natural environment. Reference [4] estimates the human capital index of the region using four indicators: education capital, human capital, health capital, and social capital. Reference [5] assesses human capital by the subjects of Russian Federation, including components such as demography, education, employment, science, and social culture. Reference [6] describes an indicator for assessing the human capital of an industrial region that integrates six basic components: health, expertise, culture, creativity, motivation, and loyalty.

2. Assessment of the impact of various investments on the development of human capital. Reference [7] analyzes the influence of improving the quality of the education system in the country on the development of human capital. Reference [8] studies the influence of triggers for the deterioration of health of the region's population on the human capital accumulation. Reference [9] describes the influence of private direct investment in the human capital of the region on the labor productivity of individuals. Reference [10] considers the influence of targeted investments for achieving the desired birth rate, creating a training system for specialists of the required level as well as the social security system on regional human capital.

3. Assessment of the relationship between the human capital and the social and economic development of countries and regions. Reference [11] substantiates the importance of the development of human capital for the country's economic growth. Reference [12] proposes an increase in the share of production expenditures in the Russian state budget to speed up the country's economic growth. Reference [13] notes that in 1960-2011, the investment in human capital and the dynamics of production specialization were the critical economic growth factors for developed countries. Reference [14] shows that the development of human capital has become one of the crucial factors in long-term economic growth, which contributed to poverty reduction. Reference [15] describes a clear feedback between the rate of exploitation of natural resources and the level of development of human capital. Reference [16] describes the positive impact of investments in human capital by the US defense sector on the country's economic growth as a whole.

Despite a significant amount of research in this field, we can state the shortage of tools that can reasonably form the optimal investment structure that directly or indirectly affects the development of regional human capital for the maximum possible achievement of regional development indicators. When calculating the optimal investment structure, the current parameters and specifics of the region, the planning period and available resource constraints should be taken into account. Special focus should be paid to the consideration of environmental uncertainties and incomplete information that are associated with the nature of certain constraints in the formation of the investment structure and the desire of experts and decision-makers to handle verbal estimates. For example, reference [17] evaluates the existing and new approaches for the use of fuzzy logic in modeling social and economic processes. The fuzzy set approach is seen as a promising direction that allows to model the uncertainties of verbal expert estimates of the model parameters and potential risks based on the representation of parameters and functional dependencies in the form of fuzzy numbers [18]. Fuzzy optimization problems require special solution methods. However, the lack of examples of the implementation of the proposed methods and approaches in real cases of the formation of the investment structure presents considerable difficulties in their use in optimization models.

Fuzzy optimization models with fuzzy objective functions and constraints allow to vary the results when setting various exogenously established confidence levels [19]. This provides the decision maker a greater flexibility, which is especially important in the formation of the investment structure.

On the basis of the abovementioned information, the aim of this work was to develop a fuzzy dynamic model for the formation of the optimal public investment structure for the maximum possible development of regional human capital.

III. The Research Results

Currently, one of the priorities for regional development is to increase the level of expertise of human resources in the in-demand areas of activity. Highly skilled professionals are essential for creating new high-tech industries and for reducing production costs of existing enterprises through the introduction of innovative technologies that enhance labor productivity. This led to a reorientation of the financial policy of the state to utilize available resources to create favorable conditions for the development of human capital.

Thus, the model's objective function should take into account a set of indicators that characterize the development of human capital. Each indicator is assigned a target value for a given planning period.

As an objective function, let us consider the integrated index $IHC_n(t)$:

$$IHC_n(t) = \sum_{m=1}^{M}\left(\alpha_m \times \frac{y_{mn}(t)}{\hat{y}_{mn}}\right), t = 0, 1, ..., T \quad (1)$$

where α_m is the coefficient of importance of the m-th indicator of human capital; $y_{mn}(t)$ is the value of the m-th indicator of human capital of the n-th region at time t; $\hat{y}_{mn}$ is the target value of the m-th indicator of human capital of the n-th region; m is the indicator number of regional human capital, $m = 1, 2, ..., M$; n is the number of the region of interest, $n = 1, 2, ..., N$; T is the planning period.

Let us further consider the components of formula (1).

The α_m coefficients are determined expertly using verbal estimates and by taking into account experts' levels of expertise.

As an integrated system, the regional human capital consists of certain indicators. Reference [20] highlights 24 indicators for assessing regional human capital, which are systematized within six basic groups (e.g., professionalism, education, academic and innovative development, healthcare, and culture). Let us assign a vector function to each region $Y_n(t) = (y_{1n}(t), ..., y_{Mn}(t))$.

Let us consider a multi-period process. At each point in time t, regional authorities (through the regional budget) invest financial resources with the aim of social and economic development of the region in the following areas:

- national issues (x_1);
- national defense (x_2);
- national security and law enforcement (x_3);
- national economy (x_4);
- housing and utilities (x_5);
- environmental protection (x_6);
- education (x_7);
- culture, cinematography (x_8)
- healthcare (x_9);
- social policy (x_{10});
- physical education and sport (x_{11});
- mass media (x_{12}).

Moreover, these investments directly or indirectly affect the development of human capital of the region. In addition, the development of human capital of the region is considerably influenced by private investment in the following three areas: education (x_{13}), healthcare (x_{14}), and physical education and sport (x_{15}). However, there are no state regulators to control and manage private investment in the development of human capital.

For the functional description of the impact of investments on human capital performance, the following econometric relationships are specified in a similar way as described in [20] for an expanded database (the 2017 values were added):

$$y_{mn}(t+1) = p_m\left(y_{mn}(t), x_{1n}(t), ..., x_{In}(t),\right.$$

$$\left. x_{1n}(t-1), ..., x_{In}(t-1), x_{1n}(t-2), ..., x_{In}(t-2)\right)$$

$$t = 0, 1, ..., T \tag{2}$$

where $x_{in}(t)$ is the investment volume in the i-th investment direction at time t; i is the number of investment direction, $i = 1, 2, ..., I$.

However, the volume of investments in the development of human capital at time t is limited by the total budget of the region $R_n(t)$:

$$\sum_{i=1}^{12} x_{in}(t) \le R_n(t) \tag{3}$$

It should be noted that the amount of budget is determined by state authorities.

We also assume that the annual rate of increase of public investments in each direction has lower limits $\bar{a} = (a_1, ..., a_{12})$ that are associated with the required minimum amount of financial resources to maintain the environment created at the previous stage, as well as the upper limits $\bar{b} = (b_1, ..., b_{12})$ associated with the maximum possible amount of financial resources for expenditure:

$$a_i \le \frac{x_{in}(t)}{x_{in}(t-1)} \le b_i, \quad i = 1, 2, ..., 12 \tag{4}$$

As noted earlier, private investment refers to unregulated financial flows allocated for the development of human capital. However, to build a model, let us assume that the annual rate of increase of private investment by areas has lower $\bar{c} = (c_{13}, c_{14}, c_{15})$ and upper limits $\bar{d} = (d_{13}, d_{14}, d_{15})$:

$$c_i \le \frac{x_{in}(t)}{x_{in}(t-1)} \le d_i, \quad i = 13, 14, 15 \tag{5}$$

In the strategies and programs for the development of the region, the target values of the resulting human capital performance are set for the planning period of interest within the framework of strategic goals and objectives $\hat{y}_{mn}$.

Let us supplement the model with assumptions regarding the process of development of human capital:

– if one period in the model is equal to one year, most indicators of human capital for a given period cannot change significantly, i.e., the relative gain of the indicator has lower $\bar{e} = (e_1, ..., e_M)$ and upper limits $\bar{f} = (f_1, ..., f_M)$:

$$e_m \le \frac{y_{mn}(t+1) - y_{mn}(t)}{y_{mn}(t)} \le f_m, \quad m = 1, ..., M \tag{6}$$

–the degrees of achievement of the target values at the end of the planning period (at time T) should not differ significantly from the target values, i.e., the deviations of the human capital performance of the region from the target values have lower $\bar{g} = (g_1, ..., g_M)$ and upper limits $\bar{h} = (h_1, ..., h_M)$:

$$g_m \le \frac{y_{mn}(T)}{\hat{y}_{mn}} \le h_m, \quad m = 1, ..., M \tag{7}$$

Model parameter values a_i, b_i, c_i, d_i, e_m, f_m, g_m, h_m and α_m are determined based on expert estimates. The assignment of given values in the form of a crisp number is challenging. An expert finds it easier to formulate these values in the form of a verbal estimate by taking into account personal views and feelings (based on their nature, expert's experience, and problem statement). For an expert, one way to simplify the task is to use a fuzzy set approach. Therefore, we will use verbal estimates converted into fuzzy trapezoidal numbers as estimates of the coefficients of objective function and model constraints.

For linguistic variables Y = <*minimum / maximum rate of increase of public investment volumes by investment direction*>, the term set can be written as *V*(*y*) = {*about* 0; *about* 0.5; *about* 1; *about* 1.5; *about* 2}. Membership functions are given in the form of fuzzy numbers:

- *W* (*about 0*) = {0; 0; 0.1; 0.5};
- *W* (*about 0.5*) = {0; 0.4; 0.6; 1};
- *W* (*about 1*) = {0.5; 0.9; 1.1; 1.5};
- *W* (*about 1.5*) = {1; 1.4; 1.6; 2};
- *W* (*about 2*) = {1.5; 1.9; 2; 2}.

Figure 1 shows the corresponding trapezoidal membership functions.

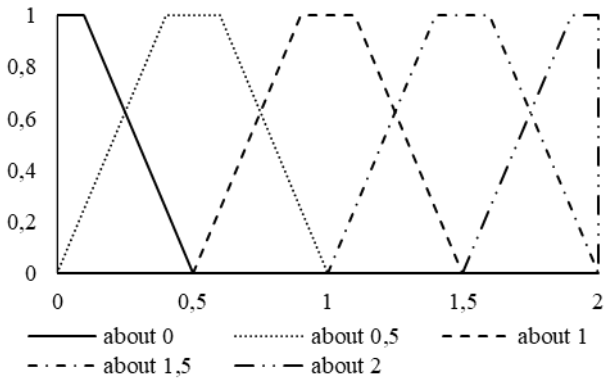

Fig. 1. System of trapezoidal membership functions on carrier [0; 2]

For the linguistic variable *Y* = <*importance of human capital performance*>, the term set can be written as *V*(*y*) = {*very low; low; below average; average; above average; high; very high*}. Membership functions are given in the form of fuzzy numbers:

- *W* (*very low*) = {0; 0; 1; 3};
- *W* (*low*) = {1; 3; 3; 4};
- *W* (*below average*) = {3; 4; 4; 5};
- *W* (*average*) = {4; 5; 5; 6};
- *W* (*above average*) = {5; 6; 6; 7};
- *W* (*high*) = {6; 7; 7; 9};
- *W* (*very high*) = {7; 9; 10; 10}.

For other model parameters, fuzziness is determined in a similar way.

It should be noted that an expert survey was conducted to determine the values of model parameters which is based on the use of opinions of independent experts and allows to determine indicator values in a given range. In cases where two or more experts are surveyed, their opinions should be consolidated. To consolidate the opinions of experts in answering the question, let us use the following formula:

$$\bar{r} = \sum_{q=1}^{Q} r^q \cdot v(s^q), \quad \bar{b} = \sum_{q=1}^{Q} \frac{b^q \cdot c^q}{\sum_{q=1}^{Q} c^q} \tag{8}$$

where r^q is the parameter estimate given by the q-th expert; $v(s^q)$ is the respondent's importance function; s^q is the estimate of the competence level of the q-th expert in assessing the value of parameter r; Q is the number of experts surveyed.

As a respondent's importance function, let us choose the following:

$$v\left(s^q\right)=\frac{s^q}{\sum_{q=1}^{Q}s^q} \tag{9}$$

This function means "smoothing" of expert estimates in proportion to competency assessments. The choice of an increasing, downward-convex function leads to an increase in the importance of opinions of more competent specialists.

To determine the coefficients of importance of human capital performance, it is necessary to normalize the estimates as follows: divide the consolidated importance estimate of the m-th indicator by the sum of all consolidated importance estimates of indicators.

Thus, we propose that the optimal allocation of public investments that directly or indirectly affect the development of regional human capital be formed using the following optimization model:

$$\begin{cases} IHC_n\left(T\right)=\sum_{m=1}^{M}\left(\alpha_m\times\frac{y_{mn}\left(T\right)}{\hat{y}_{mn}}\right)\to\max, \\ y_{mn}\left(t+1\right)=p_m\left(y_{mn}\left(t\right),x_{1n}\left(t\right),...,x_{In}\left(t\right),x_{1n}\left(t-1\right),... \\ ...,x_{In}\left(t-1\right),x_{1n}\left(t-2\right),...,x_{In}\left(t-2\right)\right), \\ \sum_{i=1}^{12}x_{in}\left(t\right)\le R_n\left(t\right), \\ a_i\le\frac{x_{in}\left(t\right)}{x_{in}\left(t-1\right)}\le b_i, \\ c_i\le\frac{x_{in}\left(t\right)}{x_{in}\left(t-1\right)}\le d_i, \\ e_m\le\frac{y_{mn}\left(t+1\right)-y_{mn}\left(t\right)}{y_{mn}\left(t\right)}\le f_m, \\ g_m\le\frac{y_{mn}\left(T\right)}{\hat{y}_{mn}}\le h_m. \end{cases}$$

The model variables used in the optimization are the annual investment volumes for certain investment areas $x_{1n}\left(t\right),...,x_{In}\left(t\right)$, $t=1,...,T$.

IV. The Results Discussion

Let us consider an example of the formation of an optimal investment structure that allows to maximize the progress towards achieving the target values of the development indicators of regional human capital using the Primorsky, Transbaikal, and Belgorod regions as examples.

The statistical data on human capital performance and investment volumes by investment directions for the regions of the Russian Federation for 2011-2017 were used as reference data, which were acquired from open sources. Reference [21] describes the clustering of regions by human capital performance. Primorsky and Transbaikal regions are assigned to the "small" cluster, which includes regions that have average human capital performance, do not have an explicit sectoral affiliation, with the dominance of small and medium-sized businesses. Belgorod region is assigned to the "industrial" cluster, which includes industrial and agricultural regions that are the main "suppliers" of permanent jobs in the country.

For dependencies (2), three types of panel data models are built using the best subsets method: end-to-end, deterministic, and spatial random effects models. Using the Wald, Hausman, and Breusch-Pagan tests, the best of the built models were selected, which were deterministic spatial effects models.

For the selected regions, let us consider the optimization of the investment structure with a planning period of three years (T = 3). The target values of the human capital performance are set as follows:

$$\hat{y}_{mn}=1{,}15\cdot y_{mn}\left(0\right) \tag{10}$$

where $y_{mn}\left(0\right)$ is the value of the m-th indicator in 2017.

Based on the expert survey results, the verbal estimates of the coefficients of importance α_m were obtained that were converted into fuzzy numbers: $\alpha_1=\left\{0{,}03;\,0{,}04;\,0{,}04;\,0{,}06\right\}$, …, $\alpha_{24}=\left\{0;\,0{,}02;\,0{,}02;\,0{,}03\right\}$.

A fragment of the consolidated model constraint values is shown in Table I.

TABLE I. Fragment of the Model Constraint Value

Lower	Value	Upper	Value
a_1	{0; 0.3; 0.5; 0.6}	b_1	{1.1; 1.8; 1.9; 2.5}
…	…	…	…
a_{12}	{0; 0.4; 0.5;0.6}	b_{12}	{1.1; 1.4; 1.6; 1.9}
c_{13}	{0.8; 0.9; 0.9; 1}	d_{13}	{1.1; 1.2; 1.3; 1.4}
…	…	…	…
c_{15}	{0.8; 0.9; 1; 1.1}	d_{15}	{1.1; 1.2; 1.2; 1.4}
e_1	{0; 0.1; 0.2; 0.3}	f_1	{0.7; 0.9; 1; 1.1}
…	…	…	…
e_{24}	{0; 0.2; 0.2; 0.3}	f_{24}	{0.6; 1; 1.1; 1.2}
g_1	{0.8; 0.9; 1; 1.1}	h_1	{1.3; 1.4; 1.5; 1.6}
…	…	…	…
g_{24}	{0.7; 0.9; 1; 1.1}	h_{24}	{1.3; 1.4; 1.5; 1.6}

In this study, the total budget for the regions under consideration was determined using the formula:

$$R_n\left(t\right)=1{,}1\cdot R_n\left(t-1\right),\quad t=1,\,2,\,...,T \tag{11}$$

Below are the results of the optimization of the structure of financial investment resources obtained using the model with the abovementioned constraints for the planning period. To identify a solution for the model using the approach presented in [22], the fuzzy mathematical programming problem was reduced to a crisp one by converting fuzzy inequalities for the objective function and constraints into crisp ones at given confidence levels. For this example, the confidence level was 0.95. The crisp problem was solved numerically by standard methods in MS Excel.

Figure 2 shows data on the allocation of total state financial resources that directly or indirectly affect the development of regional human capital over the planning period (i.e., for three years) for the regions under consideration.

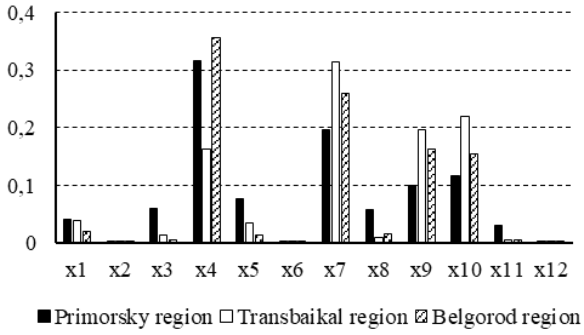

Fig. 2. Public investment structure

By analyzing the results (Fig. 2), it is clear that such directions as the national economy, education, healthcare, and social policy have the greatest impact on the development of regional human capital as a whole. Thus, for example, in Primorsky region, more than 70% of the total budget funds should be invested in these directions over the entire planning period to achieve the maximum possible progress towards achieving the target values of human capital development. For Transbaikal region, this figure should be approximately 90%. For the Belgorod region, this figure should more than 90%.

Figure 3 shows the results of using the optimal allocation of public investments and the degrees of achievement of the target values of regional human capital development systematized by six large groups.

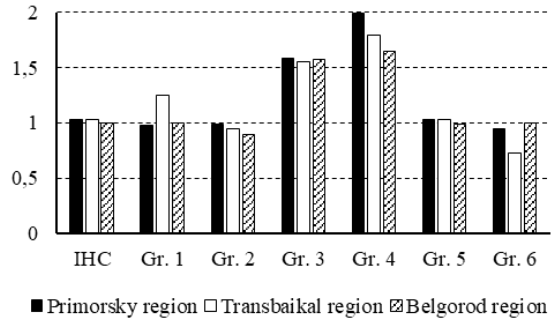

Fig. 3. Degrees of achievement of the target values of human capital development

Thus, the maximum possible values of the integrated index for the resulting public investment structures will amount to 1.03 for Primorsky region, 1.02 for Transbaikal region, and 1 for Belgorod region. At the same time, Fig. 3 shows the failure to achieve the target values for a number of groups of performance indicators of the development of regional human capital:

- for Primorsky region, indicator "Level of Professionalism" (degree of achievement 0.97) in Group 1 and indicator "Culture" (degree of achievement 0.94) in Group 6;
- for Transbaikal region, indicator "Education Level" (degree of achievement 0.94) in Group 2 and indicator "Culture" (degree of achievement 0.73) in Group 6;
- for Belgorod region, indicator "Education Level" (degree of achievement 0.89) in Group 2.

These results are achieved due to the peculiarity of the development of human capital in the regions. Several performance indicators of the development of human capital at time t=0 had high values. Therefore, given the saturation effect, an increase in the values of these indicators by 1 point requires a much greater amount of public investment.

V. Conclusion

The fuzzy dynamic model is developed that allows to create an optimal structure of public investment resources at the regional level. The objective function of the model is an integrated index that characterizes the degrees of achievement of the target values of 24 indicators of human capital development for a given planning period. Optimization variables are the investment allocation shares that directly or indirectly affect the development of regional human capital by 12 investment directions and years. The model is a fuzzy mathematical programming problem in which the uncertainty that arises when setting the coefficients of the objective function and model constraints in the form of linguistic variables based on expert estimates is modeled using a fuzzy set approach. The transition from a fuzzy optimization problem to a crisp one is carried out by setting confidence levels for the objective function and constraints. Moreover, the structure of investment allocation is affected by the choice of a certain confidence level.

The computational aspects of the proposed model are considered in terms of the formation of the optimal structure of public investment resources for Primorsky, Transbaikal, and Belgorod regions. When using the optimal public investment structures determined for the regions under consideration, the values of integrated indices are greater than or equal to unity, which indicates the achievement of most target values of the development of regional human capital.

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