Modelling a human capital of an economic system with neural networks

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Abstract. In the paper, a problem of modelling size, structure and dynamics of a human capital is solved. The research object is an economic system. The subject is a practice of applying neural networks to socio-economic parameters modelling, specifically a human capital. The objective of the paper is to build an adapted neural network algorithm with the purpose of modelling the parameter being studied. Two human capital components are estimated; these are its quantitative and qualitative properties. The key element of a quantitative property (namely, the population reproduction) has a bearing on stability of a human capital development. The quantitative property is multifold: its aspects are healthcare, culture, education and science. To estimate a human capital structure, a population is being divided onto social clusters on the basis of these aspects. As a part of the study, it was found that such mathematical modelling instrument as neural networks is very suitable for conducting a cluster analysis of a given social system. Neural networks are effective means to solve poorly formalized problems; they are tolerant to frequent changes of an environment and can be used to process a vast set of contradictory or incomplete data. The data base comprises demographic data, volume of investments into qualitative human capital properties, and socio-economic development indicators of a given economic system. A gradation of demographic elements of the society based on physical condition and cultural and educational level is built, according to which a statistical data is gathered to solve the clusterization problem. A volume of investment into a human capital is defined by budgetary costs and private investments of the people. Modelling human capital investment dynamics is performed with neural networks being applied as well. The neural network model used herein is a multilayer perceptron with sigmoid logistic activation function. Neural network modelling of predicted values of investment volumes has proved its effectiveness. An estimation of a human capital for the period of 2000-2019, as well as its forecast for years 2020-2025, is exemplified by Russian economic system. Calculations showed that the indicator being studied has been demonstrating the biggest growth rates since 2013, with an ongoing growth to be expected. Evaluated results correlate with a Russian human capital index dynamic pattern, which is defined by UN specialists, qualitatively. A proposed method of a human capital prognosis and estimation can be used furthermore to compare and estimate socio-economic state of Russia’s regions.

1. Introduction

Today, a well-being and success of every social and cultural entity depend largely on economic growth rates. A human environment gets more complicated daily. In this setting, a human capital (HC) becomes an important economic growth factor.
In current conditions, HC should be viewed more as an investment target rather than a material factor, since it becomes an asset which holds the largest capability to raise the effectiveness of the modern economy [1-3].

A HC factor comprises qualitative and quantitative properties. The main component of a qualitative property is a population reproduction; this HC property promotes its steady grow.

Alongside with the population reproduction, keeping demographic processes balanced is important too. For example, decreasing birth rate leads to a disproportion between an economically active subset of the population which takes part in public production and a subset which consumption within an economic system applies to. Well-timed determination of negative tendencies while forming a human capital qualitative property helps to nullify these negative socio-economic system development trends.

Researches which analyze modern demographic processes, forecast growth and structure of a population with birth rates, mortality rates, life expectancy and migration processes taken into account enable to shape an effective demographic strategy.

The other crucial HC property is a qualitative one. It is multifold and comprises such aspects as healthcare, culture, education and science [4, 5].

To sustain and raise HC qualitative properties, appropriate financial investments are required [6, 7].

Sustainment and development of a healthcare system enables to shorten both morbidity and mortality rates and thus to prolong an active life period of a human being. The issue of increasing an active longevity of a human has become pretty relevant lately [8]. Raising the common cultural level of a society promotes moral values development and helps to unlock the potential for creativity of a human being, which impacts an economic effectiveness positively. Investments into education and science propel presence of qualified specialists in the labor market, which enables to raise growth rates of the economy [9].

When studying demographic, economic and any other processes within the society, one of the most important instruments to conduct researches and lay prognosticative estimations is the mathematical modelling. Let’s divide the population into clusters on the basis of main HC aspects, namely health, culture and education. For clusterization, let’s use such socio-economic processes’ mathematical modelling instrument as neural networks.

In a broader sense, cluster is a group of objects which are characterized by certain common attributes, properties or qualities. The main purpose of a cluster analysis is to split an initial set of objects into such groups. The core feature of a cluster analysis in comparison to other methods is its ability to classify objects by the set of these objects’ properties. In the furtherance of a certain problem, an impact degree of every property can be reflected by their according weighting factors. This enables to devise clusterization mathematical methods, e.g. neural networks.

A landmark discovery which served the development of a cluster analysis was the perceptron, proposed by an American neurophysiologist F. Rosenblatt [10] as the result of his studies of living organisms. A perceptron is an artificial model of how brain perceives information. Modern artificial neural networks (ANN) are made out of perceptrons and thus are structurally similar to a brain, in a certain sense. The fact Rosenblatt set a problem of net’s self-learning is crucial. It provides the possibility for clusters to be organized not in accordance with a given algorithm, but out of natural conditions, which is essential in socio-economic scientific researches.

The underscore premise of the ANN theory was then built up further by virtues of studies in the field of artificial network models of a Finnish scientist T. Kohonen and an American neurobiologist and mathematician S. Grossberg [11, 12]. A possibility of building and using multilayer networks came as a result of these studies. Some noticeable researchers in the field of artificial intelligence are M. Minskiy, J. Hopfield, S. Khaikin, R. Hecht-Nielsen and others. Researches of recent vintage are presented in the papers [13-15].
2. Materials and research methods

2.1. Problem statement

To build population clusters on the basis of health condition, cultural level and educational level, let’s now take a look at the population of a given regional socio-economic system. To formalize the problem, let’s define the population as a complete set of demographic elements of the region.

From now on, a demographic element is a representative of the population – a single human of an age of τ to the moment \( t \). A total amount of demographic elements in the system is defined by the following processes: emerging (i.e. birth) of demographic elements; withdrawal (i.e. death) of demographic elements; transformation (i.e. change) of demographic elements as time passes; migration of demographic elements between clusters within the set of demographic elements of a given region; elements’ exchange between the region and an external environment (i.e. emigration and immigration).

Let \( M \) to be a complete dynamic set of demographic elements of the region. The set can be split into three clusters (in terms of their elements’ states): clusters which do not intersect, i.e. elements of one cluster can’t transform into elements of other cluster (Fig 1, a); intersecting clusters, i.e. elements of one cluster are able to transform into elements of other cluster unidirectionally and consecutively (figure 1, b); clusters which intersect and elements of which are able to transform into elements of other cluster both ways and with consecutive and parallel transitions being implemented (figure 1, b).

![Diagram](image)

**Figure 1.** The partition of a complete dynamic set of demographic elements or the region \( M \) into clusters which either do not intersect (a) or intersect (b) in time.

An example of disjoint clusters is the clusters formed on the basis of gender (i.e. men and women). An example of clusters elements of which transform one way only is an able-bodied population and a dependent population; here, elements transform as time passes due to their transition to other age stages. An example of clusters which intersect and elements of which can transform into elements of other clusters both ways is a cluster of able-bodied urban and rural population and a cluster of dependent urban and rural population.

Let’s graduate demographic elements of the society by the following properties: a health condition \( x_1 \), an educational level \( x_2 \) and a cultural level \( x_3 \). The table 1 presents graduations of these properties, in accordance with which the statistical data provided by official statistic websites is being gathered.
Table 1. Demographic elements’ properties gradation.

| Property               | Property gradation                                      |
|------------------------|--------------------------------------------------------|
| Health condition $x_1$| Healthy, With a chronic disease                        |
|                        | An employed incapacitated person (group 3 disability)  |
|                        | An unemployed incapacitated person (group 2 disability) |
|                        | An unemployed incapacitated person (group 1 disability) |
| Educational level $x_2$| With a science degree, With a higher education         |
|                        | With either secondary vocational education or incomplete higher education |
|                        | With a general education                               |
|                        | Without education                                       |
| Cultural level $x_3$   | Without a previous record                              |
|                        | With a minor crime record                              |
|                        | With an average gravity crime record                   |
|                        | With a grave offence record                            |
|                        | With an extremely grave offence record                 |

To evaluate a human capital volume of the economic system $H(t)$, the model [3] is used; according to it, the total HC value of the population engaged into social production is derived from the following expression:

$$H(t)=\int_{0}^{\infty} \sum_{i=1}^{3} \alpha_i h_i(t,\tau)e(\tau)p(t,\tau)d\tau.$$  \hspace{1cm} (1)

The functions $h_i(t,\tau)$ are normalized (per one demographic unit) qualitative properties of a HC: health $i=1$, education $i=2$, culture $i=3$. A normalized average value of a HC is defined as the following linear combination:

$$h(t,\tau)=\alpha_1 h_1(t,\tau)+\alpha_2 h_2(t,\tau)+\alpha_3 h_3(t,\tau), \quad \alpha_i \in (0,1); \sum_{i=1}^{3} \alpha_i =1,$$  \hspace{1cm} (2)

$\alpha_i$ – according weighting factors for HC properties; $h_i(t,\tau)$ values are measured in monetary units. Throughout the research, weighting factors of HC properties are evaluated as a result of solving the problem of clusterization of an economic system of the society.

In the equation (1), $p(t,\tau)$ – a distribution of demographic elements by age, the function $e(t,\tau)$ defines a share of the population of the age of $\tau$ who take part in social production in the year of $t$. The problem of demographic dynamics forecasting is thoroughly presented in the paper [4].

The evolution of every HC property follows the equation:

$$\frac{\partial h_i(t,\tau)}{\partial t}+\frac{\partial h_i(t,\tau)}{\partial \tau}= -v_i h_i(t,\tau)+s_i(t,\tau)+p_i(t,\tau).$$  \hspace{1cm} (3)

In the equation (3), the following HC properties nomenclature is used: $s_i(t,\tau)$ – normalized expenditures of the government; $p_i=p_i(t,\tau)$ – normalized private investments; $v_i(t,\tau)$ – withdrawal coefficients which are evaluated by means of the identification algorithm [4].

For the HC properties’ evolution defining equation (3), the distribution of normalized partials (which comprise governmental budgetary expenditures) by age stages $s_i(t,\tau)$ is determined from the formulas:
\[ s_j(t, \tau) = \sum_{Ni} \frac{S_{Ni}(t)}{\tau_{2Ni}} , \quad S_{Ni}(t) = \begin{cases} S_{Ni}(t, \tau), & \tau \in [\tau_{1Ni}, \tau_{2Ni}], \\ 0, & \tau \not\in [\tau_{1Ni}, \tau_{2Ni}] \end{cases} \]

Here, \( S_{Ni}(t) \) – the sums to cover the certain budget item \( N_i \) (\( N_i \) – a numbering which represents healthcare-related \((i = 1)\), education-related \((i = 2)\) and culture-related \((i = 3)\) HC development budget items). In accordance with the equation (1), these sums are to be distributed evenly to according human life age stages \([\tau_{1Ni}, \tau_{2Ni}]\) and to the amount of demographic units present at these stages.

For the equation (3), let’s define the distribution of private expenditures (aimed at HC growth) of normalized partials by age stages \( p_i(t, \tau) \) by analogy with (4) on the assumption that different expenditures to healthcare, education and culture are required during different age stages:

\[ p_i(t, \tau) = \sum_{i} \frac{P_i(t)}{\tau_{2i}}, \quad P_i(t) = \begin{cases} P_i(t, \tau), & \tau \in [\tau_{1i}, \tau_{2i}], \\ 0, & \tau \not\in [\tau_{1i}, \tau_{2i}] \end{cases} \]

During the HC investments’ volume forecasting, a neural network algorithm is applied.

2.2. Problem solving algorithm

Let’s build the neural network forecasting algorithm for an arbitrary case with an arbitrary number of variables. In fig. 2, the underlying neural network model of the algorithm is presented. The network is fully connected and multilayer; its structure is defined by number of hidden layers and by number of neurons in each of them. The neural network model represents multilayer perceptron with sigmoid logistic activation function. The neural network input data are HC budget investments’ volume \( \{S_{ij}\}_{i=1}^{n} \) and HC private investments’ volume \( \{P_{ij}\}_{i=1}^{n} \), as well as socio-economic development direction indicators \( \{I_{ij}\}_{i=1}^{n} \) [16, 17]. To account inflationary processes, a deflator index K is used.

The neural network output data is the forecast for monthly budget and private HC investments: \( \{\hat{S}_{ij}\}_{i=1}^{n} \) and \( \{\hat{P}_{ij}\}_{i=1}^{n} \) respectively.

\[ \text{Figure 2. The neural network model (D– input signal, R– output signal).} \]
Each layer of the model contains $N_p$ neurons, $p=1,...,k$. Let’s introduce the following nomenclature: $w_{ij}^p$ – a weighting factor of a connection between the signal coming out of $(p-1)$-th layer of $i$-th neuron and entering $j$-th neuron of $p$-th layer. For each layer, let’s introduce coefficients in the form of a matrix of size $(N_{p-1}+1) \times N_p$:

$$
\hat{W} = \begin{pmatrix} w_{ij}^p \end{pmatrix}, \quad p = 1,...,k; \quad i = 0,...,N_{p-1}; \quad j = 1,...,N_p. \tag{6}
$$

From an algorithmic standpoint, output values of a zero layer $u_j^0$ should be equated with input neural network signals $x_j, \ x_0 = 1$:

$$
u_j^0 = x_j, \quad j = 0,...,m. \tag{7}
$$

In other layers, output neuron values are calculated as follows:

$$
u_j^0 = 1, \quad u_j^p = \begin{pmatrix} f(d_j^p) \end{pmatrix}, \quad p = 1,...,k, \quad j = 1,...,N_p, \tag{8}
$$

where $f(d_j^p)$ is a non-linear activation function of the form $f(t) = \left(1 + e^{-\xi t}\right)^{-1}$ with coefficient $\xi$.

Let define input signal of $j$-th neuron in $p$-th layer as $d_j^p$, which is the weighted sum of its input signals:

$$
d_j^p = \sum_{i=0}^{N_{p-1}} w_{ij}^p u_i^{p-1}, \quad j = 1,...,N_p. \tag{9}
$$

Output values of the last $k$-th layer should match with $y_j$:

$$y_j = u_j^k, \quad j = 1,...,l. \tag{10}
$$

The learning process is composed of adjusting the weighing coefficients $w_{ij}^p$. The network evaluates the most possible future values of the variables from their values at certain moments in time. Statistic data on socio-economic parameters is split into two sets: a training set and a testing set, which is a retroprognosis section.

To train the net, an input data $x_q = \{x_{q1}, x_{q2},...,x_{qm}\}$ is passed and then output data is compared with ideal (i.e. actually set) values $r_q = \{r_{q1}, r_{q2},...,r_{ql}\}, \ q = 1,...,n$.

Upon the training data set, a backpropagation-driven multilayer neural network algorithm learning method is realized; it falls into the category of gradient optimization methods [14]. To determine weighting coefficients $\hat{W} = \begin{pmatrix} w_{ij}^p \end{pmatrix}$ of the net, a neural network training error is used, which is of the form:

$$E_q(\hat{W}) = \frac{1}{2} \sum_{j=1}^{l} \left(y_{qj} - r_{qj}\right)^2, \quad q = 1,...,n, \tag{11}
$$

where $y_{qj}$ corresponds to $j$-th output when inputting $q$-th image.

With inputting $q$-th observation, coefficients change as follows:
\[ \dot{W}(q) = \dot{W}(q-1) + (-\lambda \cdot \nabla E_q), \]  
(12)

where \( \dot{W}(q) \) is a state of a vector \( \dot{W} \) after training the network by \( q \)-th observation; \( \lambda \in (0;1) \) is a network training speed; \( \nabla E_q \) - a gradient of a function \( E_q(\dot{W}) \) when \( q \)-th image is being input:

\[ \nabla E_q = \left( \frac{\partial E_q}{\partial w_{ij}^p} \right), \quad p = 1, ..., k; i = 0, ..., N_p-1; j = 1, ..., N_p. \]  
(13)

Let’s express (13) in a component form:

\[ w_{ij}^p(q) = w_{ij}^p(q-1) + \Delta w_{ij}^p, \quad \Delta w_{ij}^p = -\lambda \frac{\partial E_q}{\partial w_{ij}^p}. \]  
(14)

Let’s introduce components of the vector (14) as follows:

\[
\frac{\partial E_q}{\partial w_{ij}^p} = \frac{\partial E_q}{\partial u_{ij}^p} \frac{\partial u_{ij}^p}{\partial d_j^p},
\]  
(15)

where the partial derivative \( \frac{\partial u_{ij}^p}{\partial d_j^p} \), in accordance with a derivative of the logistic function

\[ \frac{\partial f(t)}{\partial d} = \xi f(t)(1-f(t)), \]  
(13)

is of the form:

\[ \frac{\partial u_{ij}^p}{\partial d_j^p} = \xi \cdot u_{ij}^p \cdot (1-u_{ij}^p). \]  
(16)

Let’s introduce the new variable \( \delta_j^p \) as follows:

\[ \delta_j^p = \frac{\partial E_q}{\partial u_{ij}^p} \frac{\partial u_{ij}^p}{\partial d_j^p}, \]  
(17)

\[
\frac{\partial E_q}{\partial u_{ij}^p} = \sum_{i=1}^{N_{p+1}} \frac{\partial E_q}{\partial u_{ij}^{p+1}} \frac{\partial u_{ij}^{p+1}}{\partial d_j^{p+1}} = \sum_{i=1}^{N_{p+1}} \frac{\partial E_q}{\partial u_{ij}^{p+1}} \frac{\partial u_{ij}^{p+1}}{\partial d_j^{p+1}} \Delta w_{ji}^{p+1}.
\]  
(18)

Then, \( \delta_j^p \) can be evaluated recursively using the data of \((p+1)\)-th layer of the \( \delta_j^{p+1} \):

\[ \delta_j^p = \left[ \sum_{i=1}^{N_{p+1}} \delta_j^{p+1} \Delta w_{ji}^{p+1} \right] \cdot \alpha \cdot u_{ij}^p \cdot (1-u_{ij}^p). \]  
(19)

With \( p = k \), which is known from (9), (16) and (17), by equating \( u_j^k = y_{qj} \), the following form is derived:

\[ \delta_j^k = [u_j^k - r_{qj}] \cdot \alpha \cdot u_{ij}^k \cdot (1-u_{ij}^k). \]  
(20)
The last multiplier in the equation (15), according to the (9), equals to: \( \frac{\partial d_j^p}{\partial w_{ij}^p} = u_i^{p-1} \).

As a result, on the basis of the equations (14), (15), (17), we shall obtain the following difference scheme:

\[
w_{ij}^p(q) = w_{ij}^p(q-1) - \lambda \delta_j^p u_j^{p-1}.
\] (21)

To train the network, we should normalize both input and output data in their domain. Whereas \( x_j \in [a_j - h_j; b_j + h_j] \), the normalized input data is of the form:

\[
x_{qj} = \frac{x_{qj} - (b_j + a_j)/2}{(b_j - a_j)/2 + h_j}, q = 1, ..., n.
\] (22)

Whereas changing Если известно, что изменение \( i \)-th output function falls within \( [\phi_i^{\min}, \phi_i^{\max}] \), the normalized output data is of the form:

\[
\tilde{r}_{qi} = \frac{r_{qi} - \phi_i^{\min}}{\phi_i^{\max} - \phi_i^{\min}}, q = 1, ..., n.
\] (23)

To obtain actual values of the output data, a backward transformation is required:

\[
y_{qi} = \phi_i^{\min} + \tilde{y}_{qi}(\phi_i^{\max} - \phi_i^{\min}), q = 1, ..., n.
\] (24)

where \( y_{qi} \) – an actual value of the function; \( \tilde{y}_{qi} \) – an \( i \)-th output normalized value of the function when inputting \( q \)-th image to the network.

Network training quality is determined by the training error as follows:

\[
\bar{E}(\tilde{W}) = 100 \sqrt{\frac{2}{l \cdot n} \sum_{q=1}^{n} E_q(\tilde{W})}.
\] (25)

Calculation error is of the form:

\[
\bar{e} = \frac{1}{M_y} \sum_{y \in [2000, 2019]} \frac{|y^* - y|}{y},
\] (26)

where \( M_y \) – a number of set points of \( y \) indicator on the time axis; \( y^* \) – value, obtained through the model; \( y \) – actual statistic data.

3. Research results

The calculations are exemplified by the economic system of Russia. Throughout the calculations, the statistical data presented at official website of Federal State Statistic Service [18] were used. On the basis of neural network algorithm (6)-(26), certain subtasks defined in terms of economic system human capital modeling were solved: a problem of clusterization of the society of a given economic system on the basis of social elements’ property gradations and a weighting coefficient forecast \( \alpha_i \) for HC qualitative properties (i.e. health, education, culture), presented in table 1; the problem of forecasting investments into HC qualitative properties.
In the figure 3, economic system society clusterization by educational criteria results and its projections for 2025 are presented as an example. It’s apparent that population shares with higher education and science degree for the period being studied do grow. In the figure 4, weighting coefficient $\alpha_i$ (health $i=1$, education $i=2$, culture $i=3$) calculation results are presented. All three components present a favorable situation; growth rates are synchronous, therefore weighting coefficients for the period are virtually equitable (figure 3, b).

In the figure 5, the dynamics of annual budgetary investments of Russia into HC qualitative properties is presented; in the figure 6 – the dynamics of private investments of citizens. For the period of 2020-2025, these parameters were forecasted. An average annual budgetary investment growth rates for the period of 2020-2025 would comprise 0.2% for a healthcare property, 0.1% for an education property and 0.05% for a culture property. Average annual private investment growth rates for the period of 2020-2025 are figured to comprise 4.1%, 0.05% and 6.3% respectively.

In the figure 7, a convergence graph to 1% error rate is presented. In the figure 8, the Russia’s economic system HC calculation results are presented. The indicator grows; it’s forecasted to reach 135.9 tn. rub. by the year 2025.
4. Conclusion

The problem of modelling HC value which accounts a demographic structure and includes three components (namely, the education, health and culture) is solved. The model enables to perform analysis and forecast of dynamics of human capital and its components both by time and by age.

Neural network modelling was evaluated, and the prognosis of Russia’s economic system HC qualitative properties (education, healthcare, culture) was performed. It was shown that for the period being studied (i.e. years 2000-2019) and up to the year 2025 a synchronous development of these properties was observed. Neural network modeling was performed and the processes of investment into qualitative HC properties were forecasted. An increase of investments into healthcare, education and culture for the period of 2020-2025 by 1.7%, 0.1% and 6.8% respectively was observed.

The calculations showed that Russia’s HC value has been demonstrating the fastest growth rates since the year 2013, and the further growth of this indicator is expected. In the year 2019, HC value per one Russian citizen comprised about 775 thousand rubles per year.

The obtained results do qualitatively correlate with the dynamics of change of a Russia’s human development index, which is determined by UN authorities; for the period of 2000-2012 it had been growing from 0.71 to 0.79 and hereafter, up to the year 2017, remained virtually constant and close to 0.8.

The deviation of model values of investments into Russia’s HC components for the period of 2000-2019 comprised 1.4%. Neural network modelling has proven its effectiveness in solving the stated problems.

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