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DEVELOPMENT OF ASSESSMENT AND FORECASTING TECHNIQUES USING FUZZY COGNITIVE MAPS

Nowadays, no state in the world is able to work on the creation and implementation of artificial intelligence (AI) in isolation from others. AI technologies are used to solve general and highly specialized tasks in various spheres of society. In the process of assessing (identifying) the state of complex objects and objects of management analysis, there is a high degree of a priori uncertainty regarding their state and a small amount of initial data describing them. At the same time, despite the huge amount of information, the degree of non-linearity, illogicality and noisy data is increasing. That is why the issue of improving the efficiency of assessing the condition of components and objects is an important issue. Thus, the objects of analysis were chosen as the research object. The subject of research is the identification and forecasting of the analysis object.

In the research, the evaluation and forecasting method was developed using fuzzy cognitive maps. The features of the proposed method are:

– taking into account the degree of uncertainty about the object state while calculating the correction factor;
– adding a correction factor for data noise as a result of distortion of information about the object state;
– reduction of computing costs while assessing the object state;
– creation of a multi-level and interconnected description of hierarchical objects;
– correction of the description of the object as a result of a change in its current state using a genetic algorithm;
– the possibility of performing calculations with source data that are different in nature and units of measurement.

It is advisable to implement the proposed method in specialized software, which is used to analyze the state of complex technical systems and while making decisions.

Keywords: *artificial intelligence, analysis objects, complex technical systems, vague cognitive maps, uncertainty.*

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1. Introduction

Nowadays, no state in the world is able to work on the creation and implementation of artificial intelligence (AI) in isolation from others. The NATO strategy on artificial intelligence, adopted in October 2021 with the aim of accelerating the implementation of AI, interprets AI as an opportunity to achieve technological advantage, but at the same time as a source of threats and sets the following aims [1]:

– acceleration and active promotion of AI implementation;
– protection and monitoring of AI technologies and innovative capabilities, taking into account security policy considerations, such as the practical application of the principles of responsible use;
– detection and protection against threats of malicious use of AI.

AI has become widely used in solving various tasks in [1–3]:

– ecology and agriculture;
– telecommunications industry, production and energetic;
– medicine, scientific activity and education;
– security and defense of Ukraine, etc.

AI is used to increase the efficiency of data processing, processing of large data sets and to support decision making [3–5].

At the same time, despite the huge amount of information, the degree of non-linearity, illogicality and noisy data is increasing. Crisis phenomena, the current political and economic situation in the world cause global changes in all spheres of human activity, which significantly complicates the forecasting of time series based only on historical data.

In the development and future changes of time series, there is reflexivity between events, their participants and the actually predicted process (time series) between the researcher and the researched process [2]. The theory of reflexivity in the economic world suggests that the situation that has arisen affects the behavior of the process participants themselves; their thinking and behavior affect the development of the situation in which they are participants [3]. It is clear that using only one time series forecasting tool, no matter how powerful it is, it is impossible to reflect and take into account the situation and events that affect the studied process, since, let's say, the neural network works with historical data. A practical way out of the situation is the development of such methods that could operate both with cause-and-effect relationships between events and the predicted process and with the numerical values of the time series and its historical data. Therefore, it is advisable to develop a hybrid forecasting system capable of handling both qualitative and quantitative data.

Analysis of changes in the forms and methods of armed conflicts in recent decades [1–3] and trends in the development of information systems of various functional purposes [4–7] convincingly indicate the need to change approaches to:

– collection of information from various sources;
– analysis of various types of data;
– information presentation forms;
– procedures for storage and access to various data types;
– integration of disparate sources of information into a single information space.

Taking into account the above, *the aim of the research* is to develop a method of assessment and forecasting using fuzzy cognitive maps.

2. Materials and Methods

Object of research – analysis objects.

Subject of research – identification and prediction of condition objects.

Research problem – increasing the efficiency of decision making regarding the analysis object state.

Modeling was carried out using MathCad 14 (USA). Aser Aspire based on the AMD Ryzen 5 processor was used as hardware. Fuzzy cognitive maps were chosen as the basic mathematical apparatus in the proposed research to describe the objects of analysis and a genetic algorithm was used to correct the relationships between the elements of fuzzy cognitive maps.

3. Results and Discussion

3.1. The development of assessment and forecasting method using fuzzy cognitive maps. The method of assessment and forecasting using fuzzy cognitive maps consists of the following interrelated procedures.

1. *Entering initial data about the object state.*

2. *Initialization of the initial object state model.*

3. *Introduction of correction coefficients for noise and a priori uncertainty* about the object state using expressions [2].

As a rule, due to the lack of a priori information about the coefficients and the order of the differential equation, the use of a binary representation of the optimization variables becomes difficult and ineffective in the sense of finding a solution. However, when there is information about the degree of noise in the data and the degree of uncertainty about the object state, it becomes possible to increase the accuracy of constructing fuzzy cognitive maps.

4. *Construction of a fuzzy cognitive map of the object state.*

According to the accepted transition from a vector, that is, an individual, to a differential equation, the vector, taking into account the peculiarities of the chosen presentation of the solution, contains information about the order, structure and coefficients of the differential equation, which must be taken into account to improve the algorithm [8–12].

In order to build a cognitive map that reflects the dynamic properties of the situation, it is necessary to determine the scale of factor values and their increase.

To construct a factor scale, a set of linguistic values of the factor is defined and structured. While determining the linguistic values, the absolute values of the factor are used, and not its evaluations such as «large», «medium», «small». With this definition of the linguistic values of the factors of the situation, an objective standard of its meaning is set – a reference point. The assignment of an objective benchmark of the value of the factor facilitates the work of experts regarding the influence of factors and reduces expert errors.

The task of the forecast is reduced to the maxtriangular composition of the matrix of weights and the vector of initial increases of features.

This algorithm works for positive definite matrices, while in this case the elements of the adjacency matrix and increment vectors can take on negative and positive values.

The following adjacency matrix transformation rule $W=|w_{ij}sl|n\times n$ is used with positive and negative elements to a positive definite dual matrix $W=|w'_{ij}sl|2n\times 2n$:

– if $(w_{ij}sl)>0$, then:

$$w'_{i(2j-1)}s_{(2l-1)}=w_{ij}sl, w'_i(2_j)s(2l)=w_{ij}sl; \tag{1}$$

– if $(w_{ij}sl)<0$, then:

$$w'_{i(2j)}s(2l)=-w_{ij}sl,\ w'_i(2_j)s(2l-1)=-w_{ij}sl. \tag{2}$$

The initial vector of increments $P(t)$ and the vector of predictive values of features $P(t+1)$ in this case should have dimension $2n$. The rule for obtaining the initial growth vector $P'(t)$ of dimension $2n$ from the initial vector $P(t)$ of dimension n is the following:

– if $p_{ij}(t)>0$, then:

$$p'_i(2_j-1)(t)=p_{ij}(t), p'_i(2_j)(t)=0; \tag{3}$$

– if $p_{ij}(t)<0$, then:

$$p'_i(2_j)(t)=p_{ij}(t), p'_i(2_j-1)(t)=0. \tag{4}$$

In vector $P'(t)=(p_{11}-,p_{11}+,\ \ldots,p_{nm}-,p_{nm}+)$ the value of the attribute f_{ij} characterizes two elements: the element with the index 2_j characterizes the positive $p_{ij}+$, and with an index 2_j-1 is negative p_{ij} is an increase of the sign f_{ij}.

Then the double vector of increments $P'(t+1)$ for a positive definite matrix W' is determined using the following equation:

$$P'(t+1)=P'(t)W', \tag{5}$$

where to calculate the element of the vector $P'(t+1)$, the rule is used:

$$p'_{ij}(t+1)=\max_{sl}(p'sl(t)\cdot w'_{ij}sl). \tag{6}$$

The elements of vectors of increments of feature values obtained at successive moments of time $P'(t+1),...,P'(t+n)$, after transposition is presented in the form of a block matrix:

$$P_t = \left|P'(t+1)T,...,P'(t+n)T\right|. \qquad (7)$$

The rows of this matrix are the value of the increase of one characteristic at successive moments of time; the columns are the value of the increase of all the characteristics at the moment of time corresponding to the selected column. Matrix P_t is called the growth matrix and is used during the operation of algorithms for explaining forecasts of the development of the situation [13–16].

5. *Forecasting the dynamics of changes in the object state.*

A number of factors of the situation are set:

$$F = \{f_j\}, j = 1, \ldots, m;$$

$Z_j = \{z_{jk}\}$ is the ordered set of linguistic values of the i-th factor, k is the number of the linguistic value, and the scales of all X_i factors are determined.

The cognitive map (F, W) is determined expertly, where F is a set of vertices – factors of the situation, $W = |w_{ij}|$ is the adjacency matrix and the initial state of the situation as a vector of values of all factors of the situation:

$$X(0) = (x_{10}, \ldots, x_{m0}).$$

The initial vector of the increase in the factors of the situation is determined:

$$P(t) = (p_1, \ldots, p_m).$$

It is necessary to find the state vectors of the situation:

$$X(t), X(t+1), \ldots, X(t+n).$$

And also the vectors of increasing the situation state:

$$P(t), P(t+1), \ldots, P(t+n),$$

at successive discrete points in time $t, t+1, \ldots, t+n$, where t is the number of the step (clock) of the simulation.

The forecast of the development of the situation is determined using the matrix equation:

$$P(t+1) = P(t)W,$$

where (...) is the *max-product* rule: $p_i(t+1) = \max_j(p_j(t)w_{ij})$.

Vector element of the forecast of the development of the situation $p_i(t+1) \in P(t+1)$ represented by a couple:

$$\langle p_i(t+1), c_i(t+1)\rangle,$$

where $p_i(t+1)$ is the value of the increase factor, $c_i(t+1)$ is the consonance of the factor value. Cognitive consonance about the value of the factor is used to characterize the subject's confidence in the results of the simulation. At $c_i(t) \approx 1$ confidence of the subject in increasing the factor $p_i(t)$ is maximum and at $c_i(t) \approx 0$ is minimal.

The state of the situation at successive moments of time will be determined by the pair:

$$\langle X(t+1), C(t+1)\rangle,$$

where $X(t+1) = X(t) + P(t+1)$ is the vector of the state of the situation (an element of this vector $x_i(t+1) = x_i(t) + p_i(t+1)$, cognitive consonance of the value $c_i(t+1) \in C(t+1)$).

A plausible forecast of the development of the situation in this case will be determined by a pair:

$$\langle X(m), C(m)\rangle,$$

where $X(m) = (x_1(m), \ldots, x_m(m))$ is the vector of values of factors of the situation at the moment $t=m$; $C(m) = (c_1(m), \ldots, c_m(m))$ is the consonance vector of the values of the factors of the situation at the moment $t=m$.

6. *Learning a fuzzy cognitive map using a genetic algorithm.*

Let's suppose that there is a set of $3N$ lines of historical data (further – training material) about the state of concepts in the system. From the point of view of the task of forecasting based on concept increments, concept increments from the i-th iteration to $k(i+1)$ iterations constitute the initial vector of increments. In this case, the fuzzy cognitive map should show that with a similar initial increment vector, the values of the concepts will change in such a way that the results of their increase will lead to the values at $(i+2)$ iterations.

Let $A_i(t)$ be the value of the concept at time t. From the specification of the training material given above, let's consider three lines: $A_i(t)$, $A_i(t+1)$, $A_i(t+2)$.

Let's define:

$$x_i = \frac{A_i(t+1) - A_i(t)}{A_i(t)},\ y_i = \frac{A_i(t+2) - A_i(t)}{A_i(t)},$$

where x are the initial vectors of increments, y are the resulting vectors of increase.

A genetic algorithm is proposed to solve the learning task. A one-dimensional array of values is distinguished as a chromosome, in which a two-dimensional array of weights of a fuzzy cognitive map is laid out. Each value in this array is called a gene. Let's define the main steps of the algorithm:

1. For all non-zero weight values of the original map, a new non-zero weight value set by a small random is determined. The initial non-zero weight values are determined by the expert (the non-zero value can be any, its only purpose is to indicate that, in the opinion of the expert, there is a causal relationship between the two selected concepts).
2. Step 1 is repeated *Population Size* times. Therefore, the initial population of random solutions is formed.
3. A *fitness function* is determined for each chromosome (the type of fitness function is described below).
4. The pool of parents is determined by the «roulette» method.
5. «Elite individuals» are added to the pool of parents. Elite individuals in genetic algorithms mean individuals that showed the best value of the fitness function in the last several generations (one individual per generation).
6. Chromosomes that have entered the pool of parents cross over. Crossing of chromosomes A and B occurs as follows. The crossing limit is randomly determined. Let's denote the A_{l+} part of chromosome A, which consists of genes located starting from l, and A_{l-} is the part of the chromosome that is located before l. Then the result of crossing will be two chromosomes $A_{l-}B_{l+}$ and $B_{l-}A_{l+}$. The probability of crossing is determined in advance. If crossover does not occur, both parental chromosomes pass unchanged into the offspring population.
7. A new population is formed from the offspring obtained in step 6 (its size exactly matches the size of the population at the previous stage of the algorithm).

8. Mutations occur in the offspring population. In mutation, a random gene is selected and replaced with a new random value. The probability of mutation is predetermined. If there is no mutation, the chromosome is transformed into the next iteration of the algorithm unchanged.

9. The following generation parameters are determined: an elite individual (an individual with the best value of the degree of adaptability) to preserve its gene pool; the average value of the fitness of the population (only relevant for evaluating the convergence of the algorithm); the value of adaptation of an elite individual.

10. If the fitness value of the elite individual is greater than the predetermined maximum fitness value, the algorithm stops and the selected chromosome is decomposed into the adjacency matrix of the fuzzy cognitive map (training is considered complete). Otherwise, proceed to step 3.

The end.

3.2. Results of the analysis and discussion of the results. A method of assessment and forecasting using fuzzy cognitive maps has been developed. The concept of elite individuals was introduced into the algorithm to accelerate the convergence of the algorithm. The number of elite individuals is taken equal to 60, while the size of the population is equal to 100. Therefore, at each step after the 60-th generation, only 40 chromosomes from the current population have a chance to cross – the rest fill the elite gene pool inherited from previous populations.

Such a high value of the probability of mutation (usually uncharacteristic of genetic algorithms) is justified in this case, since mutations introduce genetic diversity into the population. At the same time, since an elite gene pool is used, there is no risk of irreversible loss of useful genes inherited from previous generations.

Transient processes of different systems can coincide in a certain interval, so only increasing the interval of observing the system output and increasing the frequency of taking measurements can increase the efficiency of finding a solution. On the other hand, the reason for this may be the presence of a large number of local optima and a rather strong attraction zone.

The proposed method differs from the existing ones:
- it takes into account the degree of uncertainty of information about the state of a dynamic object and the noise level of the initial data about its state;
- it creates a multi-level and interconnected description of hierarchical objects;
- it increases the efficiency of decision making while assessing the state of objects due to the search for a solution using the individuals of the population;
- it solves the problem of falling into a global extreme.

The advantages of the research include:
- calculations take into account the degree of uncertainty about the object state;
- taking into account the degree of data noise as a result of distortion of information about the object state;
- a reduction of computing costs while assessing the object state;
- the possibility of performing calculations with source data that are different in nature and units of measurement.

The shortcomings of the mentioned research should include the availability of appropriate computing power and time for calculations.

It is advisable to implement the mentioned method in specialized software, which is used to analyze the state of complex technical systems and while making management decisions.

The direction of further research should be considered the further improvement of the specified method to take into account a greater number of factors during the state analysis.

4. Conclusions

In the research, the development of evaluation and forecasting methods using fuzzy cognitive maps was carried out.

Features of the proposed method are:
- taking into account the degree of uncertainty about the object state while calculating the correction factor;
- adding a correction factor for data noise as a result of distortion of information about the object state;
- reduction of computing costs while assessing the object state;
- creation of a multi-level and interconnected description of hierarchical objects;
- correction of the description of the object as a result of a change in its current state using a genetic algorithm;
- possibility of performing calculations with source data that are different in nature and units of measurement.

It is advisable to implement the proposed method in specialized software, which is used to analyze the state of complex technical systems and make management decisions.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

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