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Development of the concept of simulation modeling of the ecological situation based on the theory of self-organization

The article is devoted to the development of a concept of simulation of the environmental situation based on the theory of self-organization. The trend of increasing temperature and sea level due to an increase in the level of greenhouse gases in the Earth's atmosphere is global. This indicates the need to predict the development of the environmental situation in order to inform the population about possible disasters for preparing people's responses, resettlement planning, psychological adaptation. To predict the environmental situation as a result of accidents and disasters, including in rail transport, an analysis apparatus for possible situations is proposed with the aim of developing recommendations for their prevention. An environmental simulation model based on the theory of self-organization was chosen as the apparatus of research. It is based on the processes of mutually agreed relations, as a result of changes in two species of wildlife (object and environment), leading to the formation of a certain orderliness of these relations. Interaction of this kind occurs in the direction of achieving the existing equilibrium state or the formation of a new balance.

***Keywords**: simulation model, environmental situation, theory of self-organization, expert assessment, equilibrium state, knowledge base.*

Introduction. To predict the environmental situation as a result of accidents and disasters, and not least in railway transport, a theoretical study of possible situations and means of their prevention is proposed using a simulation software model built on the basis of the theory of self-organization.

Justification of relevance. The 26th Conference of the UN Framework Convention on Climate Change (COC-26) was held in October-November 2021 [1].

It was called "the last chance to agree on measures that will slow down the process of global warming on the planet." Currently, 197 countries and one intergovernmental association - the European Union - are parties to the Convention.

This is the largest conference in this field in recent years. If in the zero years of the 21st century the world was faced with climate change, today it lives in an emergency mode. The decade of 2009-2019 became the hottest since the beginning of keeping relevant statistics.

According to the Paris Agreement, its participants agreed to update their plans for reducing greenhouse gas emissions every five years. However, this was not fully implemented.

The UK is pushing for a deal that would "make lignite and coal a thing of the past" and proposes to phase out internal combustion engine cars by 2040. Another direction of investment should be the work to prevent deforestation on Earth. The US and China have already pledged to become climate neutral by mid-century.

Most of the responsibility for greenhouse gas emissions lies with the rich, industrialized countries of the world.

More and more of the world's industrialized nations are committing to transform their economies in such a way that they become carbon-neutral in the next 10-30 years. But if CO_2 emissions stabilize in Europe and North America, they continue to grow in Asia and Africa. Fig. 1 shows how intensive the economic turnaround in these regions must be in order to achieve the goal of climate neutrality.

But the absolute amount of CO_2 emissions is not the only important indicator. After all, the population of the planet is growing, especially on the Asian continent, and the increase in the number of its inhabitants means an increase in consumed resources. If we correlate CO_2 emissions with the population, it turns out (Fig. 2) that the ranking of countries with the vast majority of emissions is led by the USA, Australia, Russia, Saudi Arabia, Oman, Qatar and Mongolia.

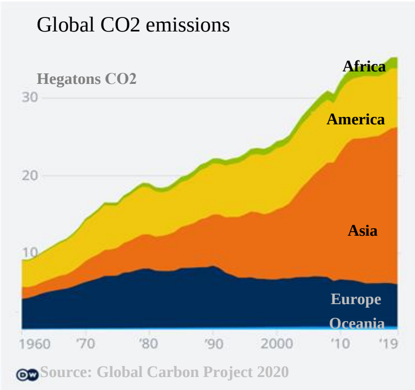

Fig. 1. **Global CO_2 emissions**

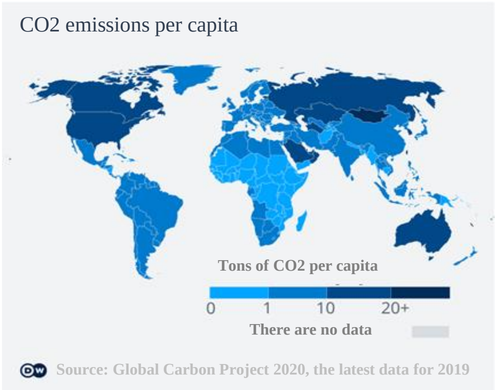

Fig. 2. **CO_2 emissions per capita**

The economic power of the state and CO_2 emissions are closely related (Fig. 3), so it is not surprising that the industrial sector is responsible for the largest share of the total volume of greenhouse gases (35%).

Deforestation has been steadily increasing over the past two decades. The first places according to this indicator are occupied by Russia, Brazil and the USA. However, compared to the period of 1990-2000, the pace of this phenomenon has somewhat slowed down. (Fig. 4). Deforestation is problematic not only because it releases CO_2 previously stored in soil and trees into the atmosphere: forests and soil are powerful sinks of carbon from the atmosphere, making them a critical tool in the fight against climate change.

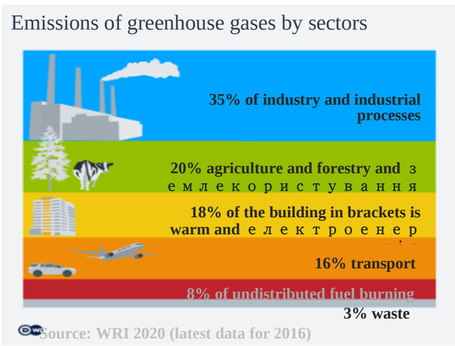

Fig. 3. **Emissions of greenhouse gases**

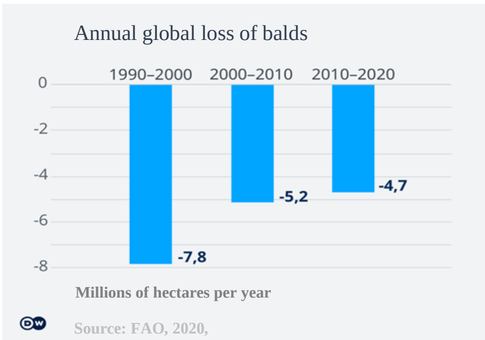

Fig. 4. **Annual global loss of bald spots**

Since the beginning of the industrialization era, CO_2 emissions from burning fossil fuels have continued to rise. At first, this was a big problem: from every ton of CO_2 produced by humans, carbon dioxide was absorbed by natural "carbon sinks" - forests and oceans. However, later on, man began to produce much more CO_2 and other greenhouse gases than the amount that the planet's ecosystems could naturally absorb. As a result, the amount of CO_2 that remains "locked" in the atmosphere is steadily increasing (see the red area on the graph - Fig. 5).

The increase in the amount of CO_2 in the Earth's atmosphere creates a kind of greenhouse effect: sunlight and heat penetrate inside, but cannot go back out. Thus, the planet is getting warmer. Compared to the average indicators of the 20th century, the global temperature rose by one degree Celsius - it increased especially intensively during the last five years (Fig. 6).

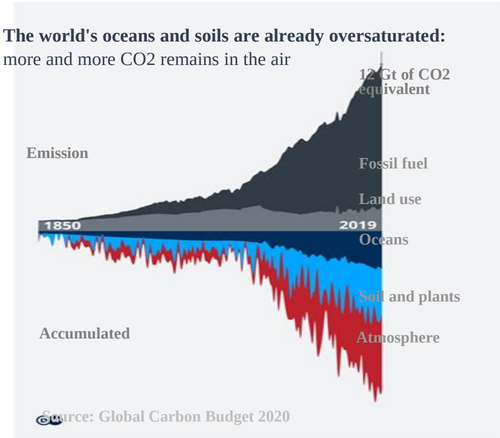

Fig. 5. **Concentration of greenhouse gases**

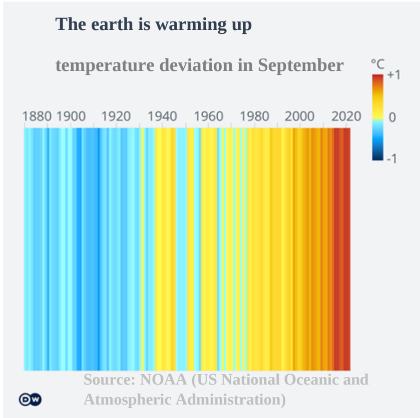

Fig. 6. **Gradient of warming of the Earth's surface**

A warming of one degree on the global average means radical changes at the local level. Warming is calculated from temperature deviations across the planet – extreme heat and extreme cold balance each other in different places.

Among the most obvious consequences of rising temperatures is a rise in the level of the world's oceans, as the melting of glaciers and ice in the mountains increases the amount of water.

According to NOAA - the US state agency for climate research - over the last 140 years, the average level of the world ocean has risen by almost 25 cm. A third of this increase has occurred in the last 25 years. The rise in the level is observed all over the world, but this process is especially fast in the Arctic, where the temperature is rising much faster than in other regions. Even more, it accelerates the property of water to expand when heated.

Formulation of the problem. The analysis shows that the tendency to increase the temperature and level of the World Ocean due to the increase in the level of greenhouse gases in the Earth's atmosphere has a global character. However, the implementation of the trend has regional features [2,3]. This indicates the need to forecast the development of the ecological situation in certain regions in order to inform the population about possible cataclysms for the preparation of people's response, resettlement planning, and psychological adaptation[4-7].

Various models (including ecological ones) built on the basis of the theory of self-organization are an effective research apparatus for solving forecasting tasks [8-10].

Types of models of ecological relationships. The basis of the proposed model is the processes of mutually determined relations as a result of the change of two species (sets) of living nature and, which lead to the formation of a certain orderliness of these relations [11].

At the same time, two assumptions were made:

a) each element has a field of interaction, within which changes are made to system-forming relationships;

b) system-forming relations of steel, for which a continuous compensatory flow is necessary.

This process can proceed to a certain limit, as it approaches the limit of the activity of the 1st set. This is due to the presence of the substance and energy necessary for existence in the incoming flow of the environment and the state of the 2nd set, which functions due to the results of the 1st set. Interaction of this kind occurs in the direction of achieving the existing equilibrium state or forming a new equilibrium.

At the heart of the process of inclusion or exit from the active state of elements are competitive relationships that are revealed; in intensifying their activities and suppressing competitors [6, 12].

The interaction of two sets can be described by a system of differential equations with respect to their number

$$\begin{cases} \frac{dN_1}{dt} = \left(\lambda_1 - \mu_1 \cdot N_1 - v_1 \cdot N_2\right) \cdot N_1; \\ \frac{dN_2}{dt} = \left(\lambda_2 - \mu_2 \cdot N_2 - v_2 \cdot N_1\right) \cdot N_2, \end{cases} \tag{1}$$

where the coefficients:

in the 1st set of elements with the previous properties:

- promotes the growth of elements;
- prevents the growth of similar elements;
- prevents the growth of elements of the 2nd set;

in the 2nd set of new elements:

– promotes the growth of elements,
– hinders the growth of similar elements,
– hinders the growth of the elements of the 1st set.

By changing the values of the parameters of the initial set of elements, all possible forms of relationships between two sets can be described by nine equations that reflect the sequence of transition from one state to another, generating a certain cycle in the phase space.

Competing relationships were considered for two sets of elements located in the same environment. Without violating generality, these considerations can be extended to the case of n sets.

The resulting system is a Volterra model of the "competition" type [13, 14].

Naturally, assumptions are made regarding the integrality of solutions and restrictions.

Questions arise: are such interactions possible, or will elements with new qualitative characteristics be replaced by the previous ones? If possible, in what proportion can they exist?

Let us analyze solutions (1) from the point of view of finding equilibrium stationary solutions with an analysis of the stability of these solutions. This system does not have direct analytical solution methods, however, it can be fully characterized using the phase space method on the plane in coordinates (N_1, N_2).

The equilibrium stationary state is realized when

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = 0. \tag{2}$$

Then from (1)

$$\begin{cases} \left(\lambda_1 - \mu_1 \cdot N_1 - v_1 \cdot N_2\right) \cdot N_1 = 0, \\ \left(\lambda_2 - \mu_2 \cdot N_2 - v_2 \cdot N_1\right) \cdot N_2 = 0, \end{cases} \tag{3}$$

All cases of invariant conditions of the process $(\lambda_1, \lambda_2, \mu_1, \mu_2, \nu_1, \nu_2 = const)$ can be obtained analytically. In the general case, invariance leads to the dominance of that process, which will have a larger ratio of the "increase in activity" coefficient to the "energy consumption" coefficient.

The effect of competing relations, arising as a result of self-limitation in the process of increasing the number of elements of the same type, can lead, depending on current conditions, either to the complete displacement of some elements by others, or to an equilibrium state with different quantitative ratios.

Of particular interest are the equilibrium states. They are largely determined by the behavior of the coefficients λ_t, μ_t, ν_t, and the stability of equilibrium relations will generally depend on their constancy. Let us assume that each element from a homogeneous population is in a certain state of active functioning or recovery. Consequently, such a state will already affect their non-equivalence with respect to any process, and affect the value of competing coefficients.

In this case, the manifestation of two opposite forms of competing relations is possible:

a) "positive" - when the achievement of a dominant position is carried out by increasing the activity of the elements of each of the sets. This leads to a faster consumption of the potential reserve, and if the required result is not achieved during the time interval of increased activity, then the dominant position is lost;

b) "negative" - when the preservation of a dominant position is achieved by actively reducing the possibility of a competing system.

In practice, these forms are analogues of positive and negative feedback.

In real conditions, both mechanisms of competitive relationships are used with the predominance of the type that allows minimizing the energy expenditure to achieve a dominant position. The adequacy of adaptive activity plays a significant role in maintaining the dominant position. When it coincides, the dominant is strengthened, and competitors are even more suppressed, and when it does not match, the dominant is weakened, and now the competing set occupies a dominant position.

Such a periodic change in the dominant position affects the value of the coefficients of intra- and inter-group competition, and, consequently, leads to a change in the equilibrium state of their numbers. This change will carry out fluctuations in a certain area, the boundaries and stability of which will depend on the change in the indicated coefficients.

According to the theory of similarity and dimensionality of H. Galileo, mathematical equations follow values or ratios. And operate with the terms: "how many times", %, trend. This more obviously characterizes the results, because absolute numbers can be converted to a dimensionless form, that is, when the variables of the equations take a value less than one, and strictly speaking - in modulus less than one. There are purely rational explanations for this. When it comes to simulation statistics, it is better to move from absolute values to relative values.

To convert the equation with the absolute variable *X* to the dimensionless form *x*, we use the formula:

$$x = \frac{X - X_{\min}}{X_{\max} - X_{\min}}, \tag{4}$$

where $X_{\max}$ and $X_{\min}$ the maximum and minimum value of *X*, respectively.

We will show the procedure for transforming the model "Competition: mutually suppressive competition (-,-)" (the first model into a dimensionless form. We define the dimensionless variables of the mathematical model (1) for N_1 and N_1, respectively, (4):

$$n_1 = \frac{N_1 - N_{1\min}}{N_{1\max} - N_{1\min}}, \qquad n_2 = \frac{N_2 - N_{2\min}}{N_{2\max} - N_{2\min}}. \tag{5}$$

Assume without loss of generality $N_{1\min} = N_{2\min} = 0$ and $N_{1\max} = N_{2\max} = N_{\max}$.

Then the formula (5) will have the form

$$n_1 = \frac{N_1}{N_{\max}}; \quad n_2 = \frac{N_2}{N_{\max}} \tag{6}$$

From (6) it is obvious that $n_1, n_2 \in [0,1]$ and

$$N_1 = n_1 \cdot N_{\max},\ N_2 = n_2 \cdot N_{\max}, \tag{7}$$

Substituting (7) into the equation for model 1, we obtain

$$\begin{cases} \dfrac{d(n_1 \cdot N_{\max})}{dt} = (\lambda_1 - \mu_1 \cdot n_1 \cdot N_{\max} - \nu_1 \cdot n_2 \cdot N_{\max}) \cdot n_1 \cdot N_{\max}; \\ \dfrac{d(n_2 \cdot N_{\max})}{dt} = (\lambda_2 - \mu_2 \cdot n_2 \cdot N_{\max} - \nu_2 \cdot n_1 \cdot N_{\max}) \cdot n_2 \cdot N_{\max}. \end{cases} \tag{8}$$

By making simple transformations and labeling

$$\mu_i \cdot N_{\max} = \mu_i' \ \nu_i \cdot N_{\max} = \nu_i', (i=1,2). \tag{9}$$

We will get the mathematical model "Competition: mutually overwhelming competition (-,-)" in dimensionless form

Carrying out similar transformations with all other options of interaction models from table.1, after transforming them into a dimensionless form, we will obtain mathematical models of interaction in a dimensionless form, as shown in table.1.

We present in Table 1 a list of models of different modes of interaction of two self-organizing sets, with an indication of the effect of the number of one species on the rate of change in the number of another.

Table 1. **Types of self-organized models of joint interaction in dimensionless form**

Type of interaction	Influence: 2nd species on the 1st	Influence: 1st species on the 2nd	Mathematical model
1	2	3	4
1. Competition: mutually superior competition	–	–	$\begin{cases} \dfrac{dn_1}{dt} = (\lambda_1 - \mu_1' n_1 - \nu_1' n_2) n_1; \\ \dfrac{dn_2}{dt} = (\lambda_2 - \mu_2' n_2 - \nu_2' n_1) n_2. \end{cases}$
2. Amensalism: one-sided dominant competition	–	0	$\begin{cases} \dfrac{dn_1}{dt} = (\lambda_1 - \mu_1' n_1 - \nu_1' n_2) n_1; \\ \dfrac{dn_2}{dt} = (\lambda_2 - \mu_2' n_2) n_2. \end{cases}$

Continued table. 1.

1	2	3	4
3. Parasitism (predation): "request - satisfaction"	–	+	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \nu_1' n_2) n_1; \\ \frac{dn_2}{dt} = (-\lambda_2 + \nu_2' n_1) n_2. \end{cases}$
4. Commensalism: one-sided positive competition	0	+	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \mu_1' n_1) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \mu_2' n_2 + \nu_2' n_1) n_2. \end{cases}$
5. Neutralism: balance	0	0	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \mu_1' n_1) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \mu_2' n_2) n_2. \end{cases}$
6. Amensalism: one-sided dominant competition	0	–	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \mu_1' n_1) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \mu_2' n_2 - \nu_2' n_1) n_2. \end{cases}$
7. Parasitism (predation): Batesian mimicry	+	–	$\begin{cases} \frac{dn_1}{dt} = (-\lambda_1 + \nu_1' n_2) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \nu_2' n_1) n_2. \end{cases}$
8. Commensalism: one-sided positive competition	+	0	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \mu_1' n_1 + \nu_1' n_2) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \mu_2' n_2) n_2. \end{cases}$
9. Mutualism: joint positive activity	+	+	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \mu_1' n_1 + \nu_1' n_2) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \mu_2' n_2 + \nu_2' n_1) n_2. \end{cases}$

The concept of computer simulation of the interaction of two sets.

For a set of two interacting sets, four levels of simulation modeling complexity are proposed, which are described in Table 2.

Algorithms of the model. Figures 7-10 show the generalized algorithms that form the basis of the process modeling system under study. The method proposed by the authors was called SRS (Selective Rapid Scan). The sequence of actions is described in Table 2.

Table 2. **Levels of simulation modeling of a self-organizing ecological community from two sets**

Level	Essence of modeling
Level 1	*Partial debugging (3-4 models).* The need for a level is to adjust the values of the coefficients of the models. The starting model is not important here. The task of this stage is to model situations for different ratios of coefficient values by changing them and obtaining a numerical solution of the corresponding equation - to make sure of the correctness of the results of the implementation of a separate model under certain conditions, to make a transition from one model to another [15]. For this, it is enough to use 3-4 models from Table 1. Model1 modeling sequence is formed. Values and ratios of model coefficients are worked out. A depot is introduced in Model1. The simulation results are analyzed.
Level 2	*Debugging is complete according to a fixed sequence of model activation.* The starting model and one of the variants of the activation sequence are selected. All nine models from Table 1 must be activated. The Level1 sequence is taken as the initial sequence. The simulation results are analyzed, and the numerical characteristics of the models are adjusted.
Level 3	*Formation of the modeling complex* The starting model is changed and 3-4 activation sequences of all nine models from Table 1 are generated. One of the modeling options is with Level2. The main task is to check the performance of the modeling complex and its verification. Description of the simulation complex and development of instructions for the user (experimenter).
Level 4	*Adequacy check* The complex is being adapted to real conditions. For this, it is desirable to choose a real, investigated and well-described case of violation of environmental safety. It can be a catastrophe or a transport accident with damage to the natural environment. The process of eliminating the consequences of a disaster or accident is recorded. An accident is simulated and the process dynamics are compared with real data.

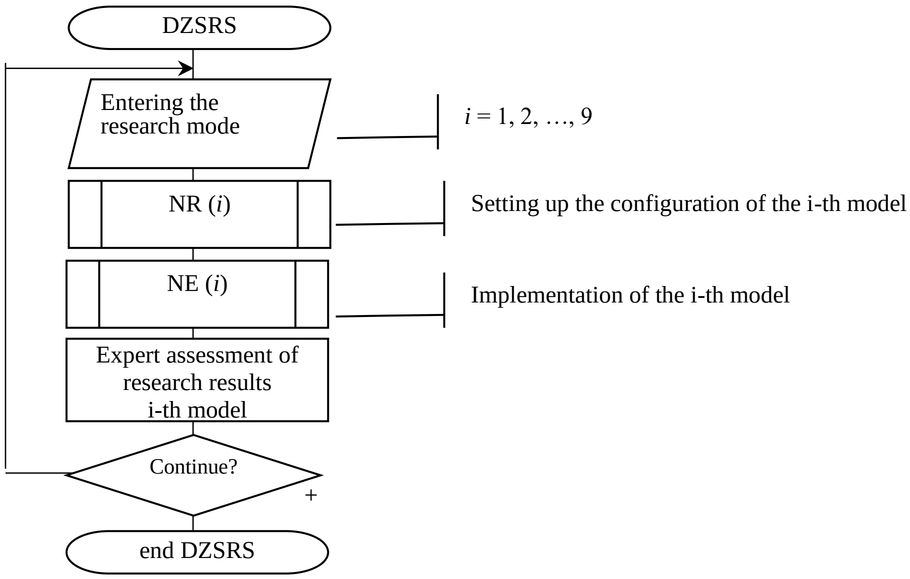

Fig. 7. **Manager of the software complex**

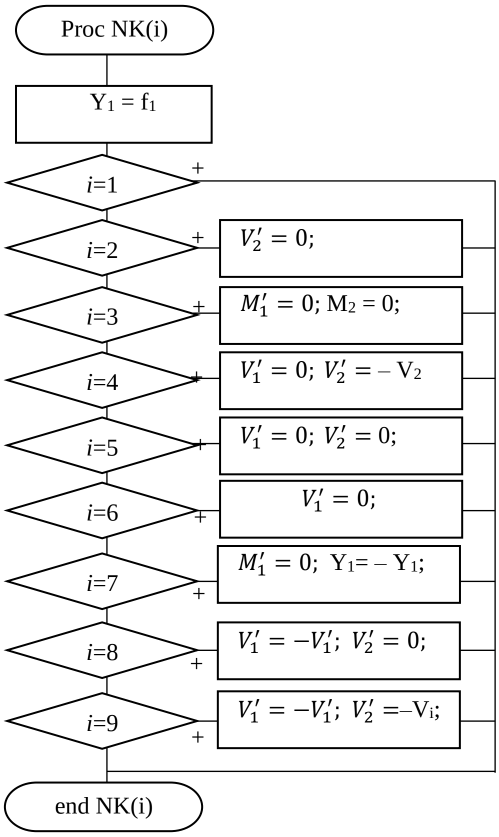

Fig. 8. **Model configuration settings (transition implementation algorithm)**

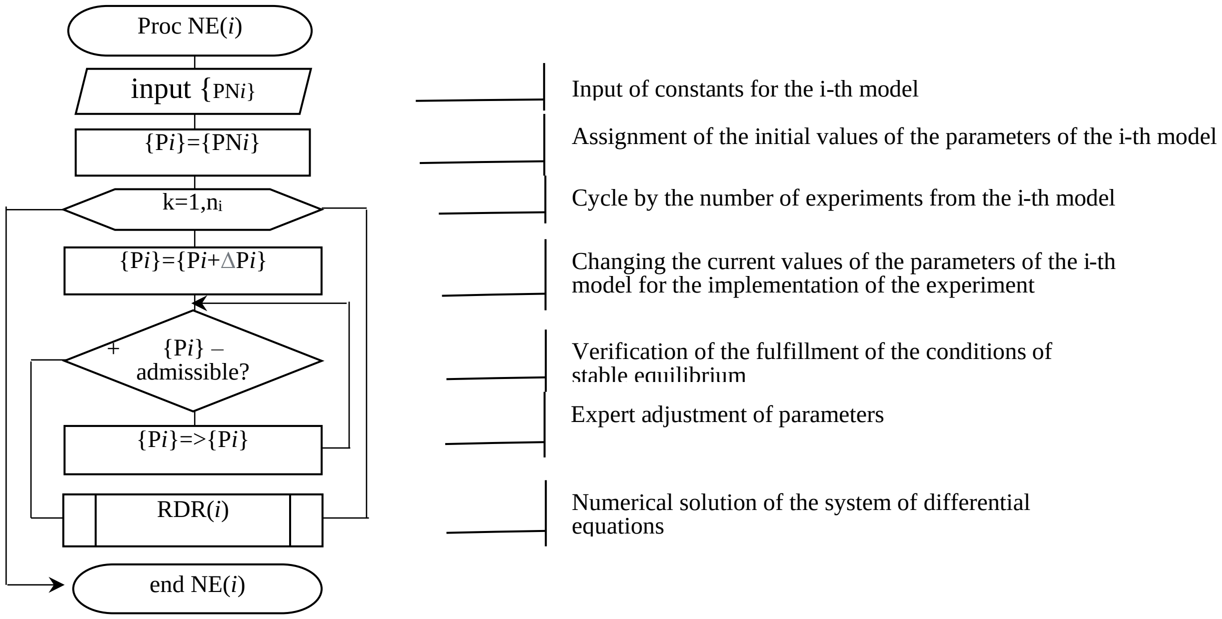

Fig. 9. **Implementation of the study of the i-th model (general case)**

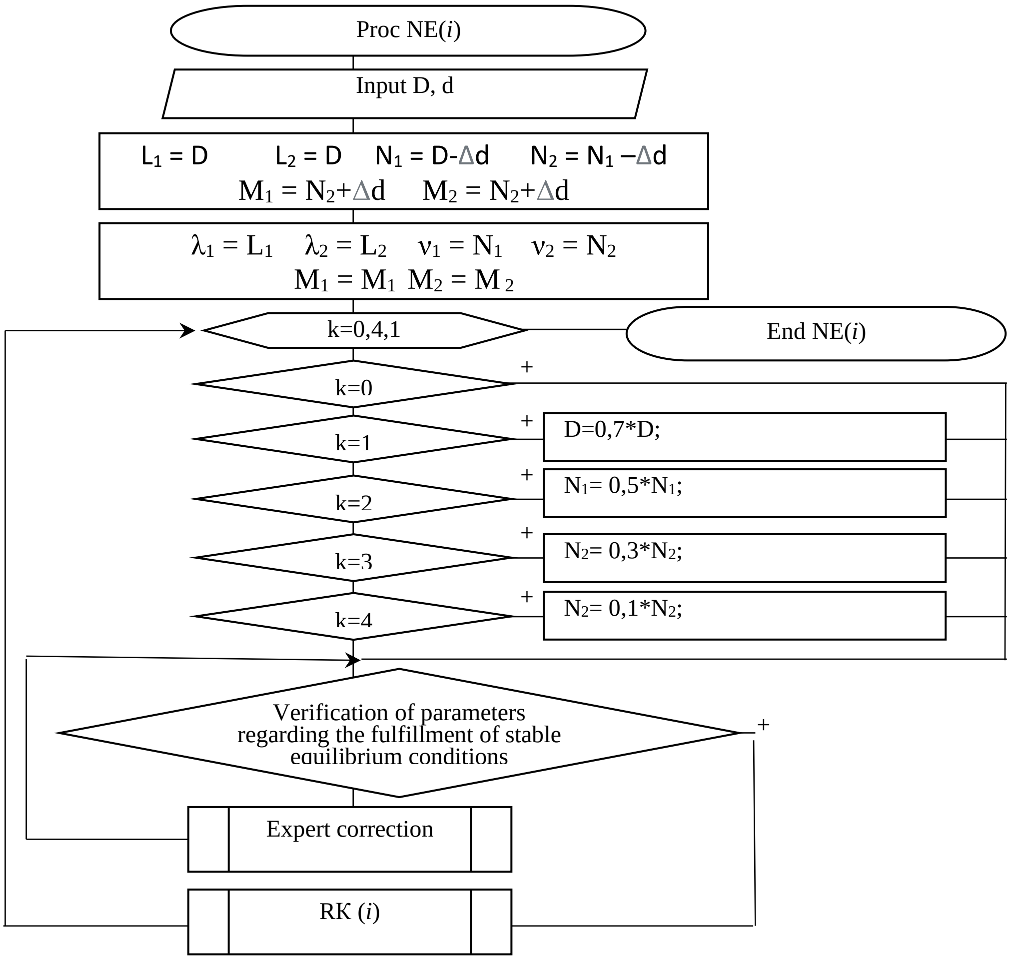

Fig. 10. **Implementation of the studio of the i-th model (general time)**

Conclusions. Note:

- conditions of competition arise in the process of self-organization;

- competitive relations lead to dismemberment of the initial complex of multiparametric system-forming relations into groups with a more simplified variation, but with a more significant manifestation of certain indicators in them;

- as a result of the principle of isomorphism, the preservation of equipotential states leads to the sequential activation of the elements of the system, and therefore to the continuous change of their state and the limits of this change.

We choose a real investigated and well-described case of an accident on railway transport with damage to the natural environment. This definitely leads to a violation of environmental safety.

The consequences of this case are recorded. Anomalous process is described by means and terms embedded in the modeling system. Scenarios predicted with the help of expert evaluation are played out.

The obtained results regarding the dynamics and consequences of the processes are compared with real data. In this way, the knowledge base is filled with certain information, the use of which will allow preventing unforeseen life situations in the future.

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Розробка концепції імітаційного моделювання екологічної ситуаціїна основі теорії самоорганізації

Стаття присвячена розробці концепції моделювання екологічної ситуації на основі теорії самоорганізації. Тенденція до підвищення температури та рівня моря через збільшення рівня парникових газів в атмосфері Землі є глобальною. Це свідчить про необхідність прогнозування розвитку екологічної ситуації з метою інформування населення про можливі катастрофи для підготовки людей до реагування, планування переселення, психологічної адаптації. Для прогнозування екологічної ситуації внаслідок аварій і катастроф, у тому числі на залізничному транспорті, запропоновано апарат аналізу можливих ситуацій з метою розробки рекомендацій щодо їх запобігання. В якості апарату дослідження обрано імітаційну модель навколишнього середовища на основі теорії самоорганізації. В його основі лежать процеси взаємоузгоджених відносин, що виникають в результаті зміни двох видів живої природи (об'єкта і середовища), *що призводить до формування певної впорядкованості цих відносин. Взаємодія такого роду відбувається в напрямку досягнення існуючого стану рівноваги або формування нового балансу.*

Ключові слова: *імітаційна модель, екологічна ситуація, теорія самоорганізації, експертне оцінювання, рівноважний стан, база знань.*