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Feasible approach to modeling of ecological component of the sustainable development paradigm

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Abstract

The paper contains the description of the feasible approach to modeling and forecasting of ecological processes that are the component of the sustainable development paradigm. The suggested mathematical apparatus is based on the statistical methods and comprises hidden Markov models with the linguistic modeling.

Keywords: modeling, forecasting, ecological processes, mathematical apparatus, hidden Markov models, linguistic modeling.

According to the definition suggested by the Centre "For our common future" ("For our common future"), that has been working in Geneva since 1988, and the United Nations Conference in Rio de Janeiro (1992), the sustainable development is understood as the kind of development that "satisfies the current needs, but does not compromise the abilities of the future generations to satisfy their own needs", or that provides "the high quality of environment and the healthy economy for all nations". Therefore, the problem of the sustainable development is the problem of the mankind salvation from the consequences of its own activity that, by the end of the 20th century, have become critical and manifested themselves in desertification, pollution of the atmosphere, oceans and soil, rapid population growth, poverty, starvation, dangerous diseases, etc. The issues of scientific knowledge and education, industry and innovation technologies, ecological, social and medical problems, international relations and political events and many other phenomena of modern life have intertwisted into the single interrelated unit. The consciousness of the situation and the search of the

Figure 1. The triune concept of the sustainable development

reasonable solutions to the problem have become an urgent matter. It requires focused attention not only on a global, but also on a national, regional and local basis [1].

Usually, the sustainable development paradigm is presented in the following way (Fig. 1).

The growing rate of exploitation of natural resources, economic decline of the economies in transition raise up the risk of the technogenic disasters, keep the countries from spending considerable efforts and resources necessary for the implementation of measures to reduce the environmental impact. To accomplish the purpose of the sustainable development the specific mechanisms for its implementation are required. The development and application of the "environmental assessment" system for the assessment of the transition to the sustainable development is of considerable significance in the world practice. The most important are the two of its modes (local and strategic) that nowadays are the well-established mechanisms of revelation and prevention of the environmental consequences of the human induced activity (refer to Fig. 2) [2].

However, for better understanding of the ecological component of the sustainable development paradigm, it is necessary to analyze some natural phenomena and biospheric processes and their interaction in the "man-environment" system. We will pay careful attention to environmentally hazardous processes.

Environmentally hazardous processes are generally understood as exogenous and endogenous (anthropogenic), short-term and long-term impacts on the ecosystem as a whole or on its particular element, leading to the violation or problems of its performance that in its turn disrupts the man-environment balance.

1. Endogenous (anthropogenic) impacts are caused by anthropogenic activity (pollution by harmful organic and non-organic substances of all kinds of the environment: the atmosphere, surface waters, water-saturated underground layers, soil, animate environments; noise and electromagnetic pollution of the atmosphere; light pollution; flooding of soils and slopes; ozone depletion and creating conditions for the greenhouse effect). They may be controlled and, in some cases, reduced or even prevented.

2. Exogenous impacts are the manifestations of the outer space and internal geological processes and changes (solar cycles, hurricanes, tropical cyclones, monsoons, volcanic activity, global warming as a result of the precession of the Earth's axis, and finally, the asteroid hazard). They are purely objective, cannot be controlled, but may be observed and forecasted. Therefore, it is possible to develop a set of measures to minimize the damages or mitigate the consequences.

It becomes clear from the mentioned earlier that the environmentally hazardous processes are of various nature and types. Also, it is evident that "not everything depends on a man".

In Fig. 3 there is a schematic classification of the environmentally hazardous processes [3].

The solar activity (Fig. 4) is a special type of an exogenous impact on the geological and biochemical processes taking place on Earth. The index for the solar activity characteristics, so called Wolf number, Zurich number or the relative sunspot number is calculated by the

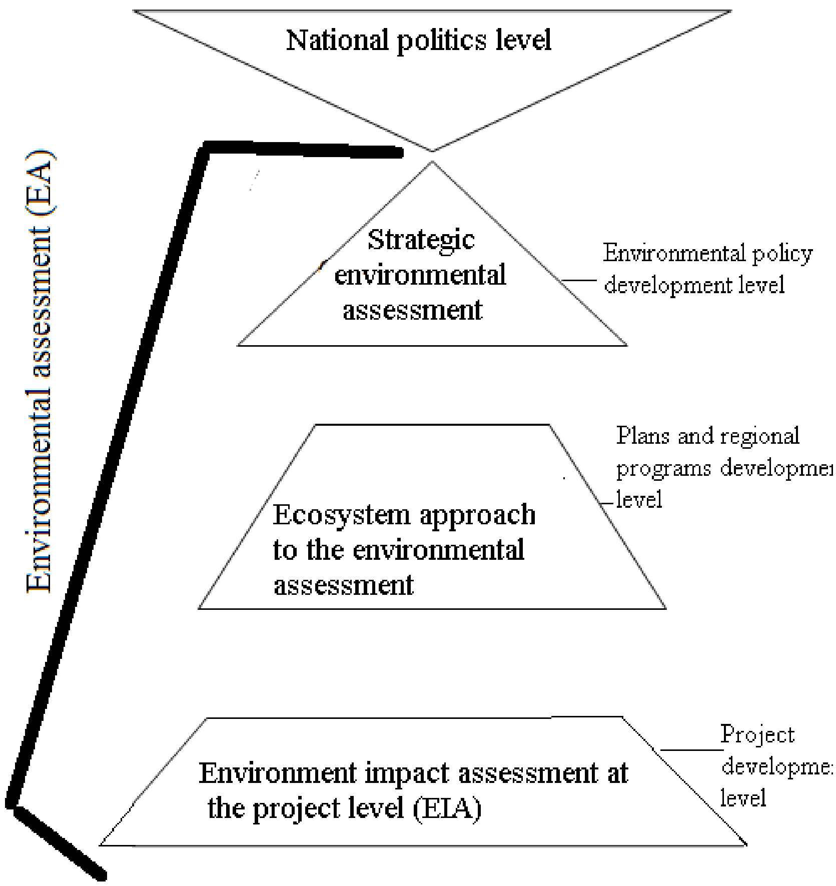

Figure 2. Environmental assessment system (EA)

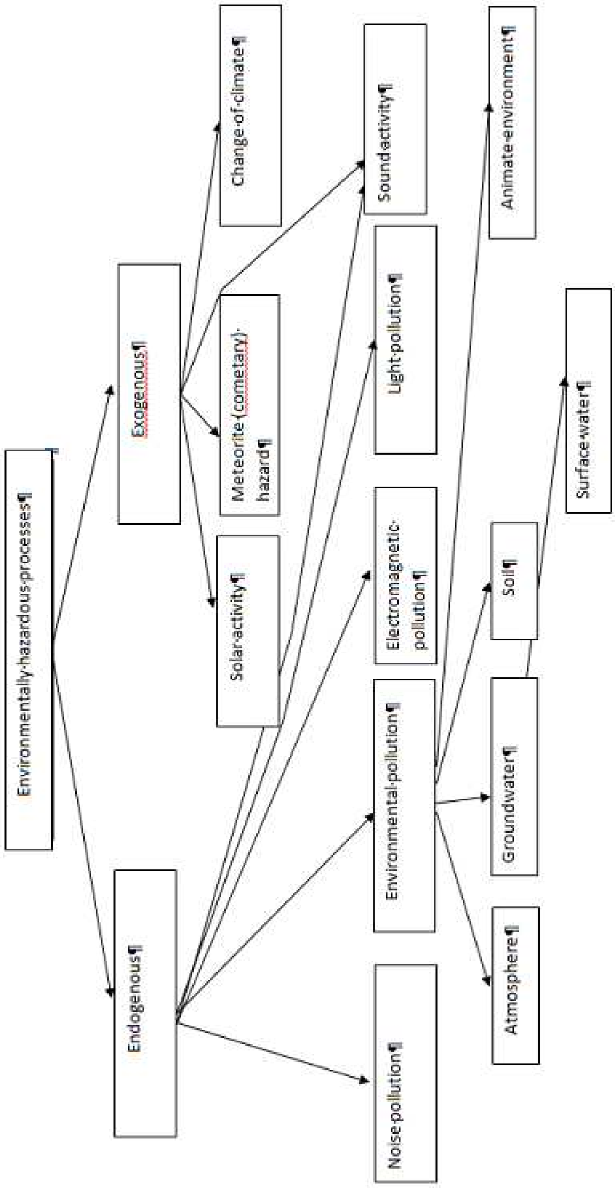

Figure 3. Environmentally hazardous processes classification

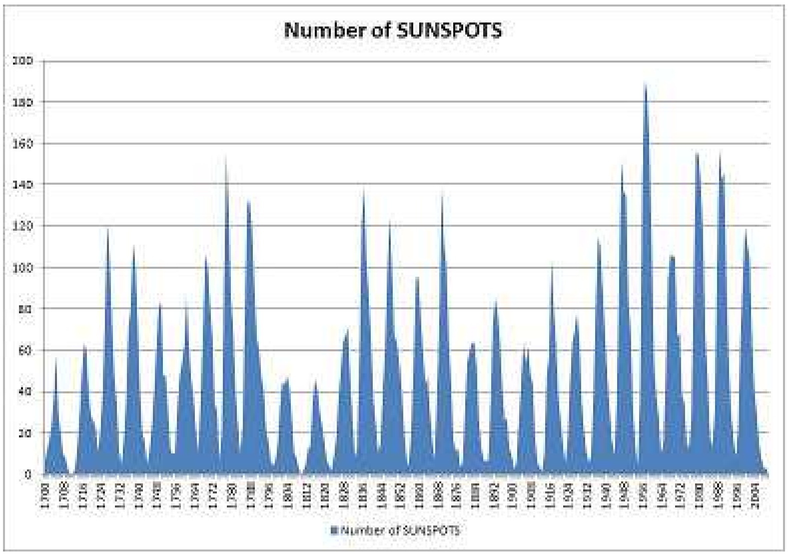

Figure 4. Solar activity cyclical change. Source: US National Centre for Environmental Information site

following formula of $R = k \cdot (f + 10 \cdot g)$, where R is the Wolf number; f is the total number of sunspots on the visible sun hemisphere; g is the number of sunspot groups; k is the multiplier (less than 1) that takes into account the total contribution of observing conditions, the telescope type and that is observed by the standard Zurich numbers.

According to the observation data for the last 304 years, the cycle length in actual practice varies from 8.5 to 14 years between the proximate minimums and from 7.3 to 17 years between the proximate maximums. The connection between the solar cycles and the increased occurrence of land slides has been proved. The most adverse impact is on that of the innovate technology effects, high-frequency operating devices, such as mobile communications, satellites (and also the related navigational safety problems), etc. Solar radiation is the source of the motion in the atmosphere-ocean system. The force, that the solar radiation generates, produces buoyancy – the source of motion in the atmosphere. It determines the nature of hurricanes, tornadoes, tsunamis and other destructive processes. Also, the solar activity influences the proliferation of some diseases, increases the frequency of traffic accidents, etc.

The climate change caused by the global warming is not only the result of increased greenhouse gases concentrations (especially, carbon dioxide) in the atmosphere, but also the result of the next cycle of the precession of the Earth's axis, thus it has an exogenous cause and it will be intensified in the near future. Although, according to Kh.Y. Shelnhuber [4], Antarctic and Greenland's ice sheet, Sahara desert, Amazonian rainforest, Asian monsoon system, Gulf Stream and six more "weak spots" of Earth influence the climate, and in the case of at least one of them undergoing changes, the ecological disaster (of the continental level) will be inevitable, the risk may be decreased by reducing the emission rate of gases mentioned earlier.

Considering the literature [3], we can define two principal directions and accordingly, two methodological approaches to the mathematical modeling of the dynamics of the environmentally hazardous processes of various nature. The first approach comprises dynamic-computed approaches based on computational methods for solving various kinds of differential equations that describe the basic laws of physics, and also atmospheric and hydrodynamic processes. They are focused on solving the following basic problems of the most important spatiotemporal patterns of the current natural processes:

- Exposure of the current spatiotemporal interrelations between various atmospheric processes in the observation dynamics;
- Natural processes modeling for the forecasting of their development dynamics.

The second approach, comprising empirical dynamic-statistical approaches based on the use of the long-term field measurement statistics, belongs to the international system for the analysis and forecasting of the ecosystem components. They are focused on the exposure of the basic spatiotemporal patterns typical of the atmospheric processes over decades. The main purpose of these approaches is, in fact, the establishment of deep spatiotemporal correlations between various natural processes based on the long-term statistics. Depending on the purposes of the study it is necessary to perform the development of the mathematical apparatus for the analysis of the dynamics of the environmentally hazardous processes based on either dynamic-computed or dynamic-statistical approaches, taking into account the specific peculiarities and properties of the processes.

Besides, there is the third type of processes that cannot be modeled with the help of dynamic-computed methods, and due to the absence of a peculiar particular periodicity (daily, monthly, annual or another permanent periodicity) they are difficult to describe using empirical-statistical methods. Therefore, the problem of the development of the process analysis and the development of the forecasting methods of such processes for the information support of the environmental situation control and monitoring system is relevant.

To sum up, the conducted analysis allows for the conclusion that the environmentally hazardous processes are characterized by the complex interrelations, interdependencies and interactions of various factors and causes. They have the following characteristic properties and peculiarities:

- The heterogeneousness and diversity of causes and factors and an activity that causes them;
- The spatial distribution of the triggering events, temporal and spatial uncertainty of the growth dynamics and their impact on the eco-surroundings;
- The nonstationarity of properties and ambiguity of their characteristics.

These properties and peculiarities determine the practical relevancy of studying of all the variety of characteristics, interrelations, interactions, interdependencies of the diverse factors and causes of the environmentally hazardous processes on the basis of the single systematic approach from the perspective of achieving the globally defined objective of the environmental situation management – early prevention and (or) minimization of the adverse effects of their action. However, the analysis shows that nowadays the various types of natural and technogenic environmental processes, their causes, progress, consequences and the sphere of the action are studied separately, without regard to interrelations, interdependencies, and interactions.

Such an approach does not consider some factors of primary importance that influence the active processes, their adverse impact level, the possibility and effectiveness of its prevention.

Considering all of the above-mentioned, we propose the feasible mathematical apparatus that may be used for the forecasting of the environmental processes of all three types [5].

Hidden Markov models (HMM). The following diagram (Fig. 5) shows the general structure of HMM. Ellipses are the variables with the random value. Accidental variable $x(t)$ corresponds to the value of the hidden variable at time t. Accidental variable $y(t)$ is the value of the variable under an observation at time t. The arrows on the diagram stand for the conditional dependences. As it can be seen from the diagram, the value of the hidden variable $x(t)$ (at time t) depends only on the value of the hidden variable $x(t-1)$ (at time $t-1$). It is called the Markov property. However, at the same time the value of the variable $y(t)$ under an observation depends only on the value of the hidden variable $x(t)$ (at time t).

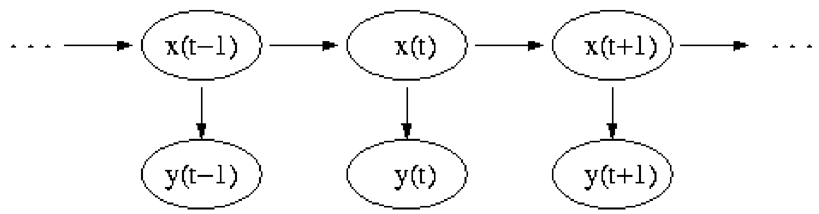

Figure 5. Solar activity cyclical change

The probability of observing the sequence $Y = y(0), y(1), ..., y(L-1)$ of the length L is $P(Y) = \sum_X P(Y/X) \cdot P(X)$.

Here, the sum runs over all possible sequences of hidden points $X = x(0), x(1), , x(L-1)$.

The basic Markov models may be described through the following variables: N is the number of conditions; T is the number of observations; $\theta_{i=1,\ldots,N}$ is the parameter for the observation of the relations between conditions; $\phi_{i=1,\ldots,N;j=1,\ldots,N}$ is the probability of transfer from condition i to condition j; $\phi_{i=1,\ldots,N}$ is N-dimensional vector consisting of j vectors $\phi_{i=1,\ldots,N;j=1,\ldots,N}$; $x_{t=1,\ldots,T}$ is the condition of the observation in a time t; $y_{t=1,\ldots,T}$ is the result of the observation in a time t; $F\left(y/\theta\right)$ is the probability distribution function of observations parameterized by θ.

The result of the environmental process observation with the help of HMM is the sequence of conditions the system undergoes during the time of observation.

Markov model of weather with three conditions will be used as an example. We will consider that the observations are made daily (for example, at noon), the weather may have one of the following conditions:

- S1 – rain (snow);
- S2 – cloudy;
- S3 – clear.

The weather on the day t is described by one of the abovementioned conditions, and the transition-probability matrix has the following form:

$$A = \begin{pmatrix} a_{ij} \end{pmatrix} = \begin{pmatrix} 0,4|0,3|0,3 \\ 0,2|0,6|0,2 \\ 0,1|0,1|0,8 \end{pmatrix}. \qquad (1)$$

Thus, having the process model in the form of the probability matrix and the start state probability matrix, we can calculate any condition sequence probability, that is any observation probability.

Linguistic modeling. According to the specific rules the numeric values are replaced with the symbols. The forecasting is made through the search of the symbol strings and their correlation with the strings from the observation database. Obtained symbols make up the V alphabet from which, in its turn, the words are formed.

Herein, the grammar (or formal grammar) is understood as the way of description of a formal language, that is the discrimination of a certain subset from the whole set of words of a certain finite alphabet.

The forecasting is performed with the help of a stochastic context-free grammar. Stochastic context-free grammar is the context-free grammar in which each deduction rule has a corresponding probability.

Context-free grammar G is the tuple (N, T, P, S): $S \in N$; N and T are the bounded disjoined sets; P is a finite subset $N \times (N \bigcup T)$.

Herein, the following names are used: N is the nonterminal set, T is the terminal set, P is the deduction rules set. Rules $(\alpha, \beta) \in P$ are specified as $\alpha \to \beta$. The left part of the deductive rule must contain one variable (nonterminal symbol). Formally, $\alpha \in N$, $\beta \in (N \cup T) \star \alpha \in N$, $\beta \in (N \cup T)^{\star}$, $\mid \beta \mid \geq 1$ should be realized.

In stochastic context-free grammars the deduction rules correlate with the probability of use:

$$\rho : \mathbf{p} \to \mathbf{R}, \tag{2}$$

where

$$\sum_{\mathbf{p_r} \in \mathbf{P_r}} \rho\left(\mathbf{p_r}\right) = \mathbf{1}. \tag{3}$$

It is necessary to combine both methods to improve the accuracy of the forecast.

Conclusion. Thus, we proposed the mathematical apparatus that might be used for the modeling and forecasting of the environmental processes of the sustainable development paradigm. The common problem of the statistical methods is the lack of the historical information. However, the mankind is engaged in the monitoring of the environment, observation of the weather and natural processes throughout the life. Therefore, the use of the statistical methods in particular is fully justified.

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