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SITUATION FORECASTING AND DECISION-MAKING OPTIMIZATION BASED ON USING MARKOV FINITE CHAINS FOR AREAS WITH INDUSTRIAL POLLUTIONS

G.V. Getun[1],
Ph D. in Technical Sciences, Professor, Professor at the Department of Architectural Structures
Y.P. Butsenko[2],
Ph D. in Physics&Mathematics, Associate Professor, Associate Professor of Mathematical Analysis and Probability Theory Department
V.A. Labzhynsky[2],
Ph.D., Associate Professor, Associate Professor of Energy Processes and Systems Design Automation Department
O.I. Balina[1],
Ph D. in Technical Sciences, Associate Professor, Associate Professor of Design Information Technologies and Applied Mathematics Department
I.S. Bezklubenko[1],
Ph D., in Technical Sciences, Associate Professor, Associate Professor of the Design Information Technologies and Applied Mathematics Department
A.V. Solomin[2],
Ph D. in Physics&Mathematics, Associate Professor, Associate Professor of the Biosafety and Human Health Department

[1]*Kyiv National University of Construction and Architecture*
31, Povitroflotsky Ave., Kyiv, Ukraine. 03680

[2] *National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"*
37, Peremohy Ave., Kyiv, Ukraine.03056

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The paper proposes a methodology for modeling engineering-within-nature complex systems (further, "systems"), which will be helpful for researchers and operators of complex technical systems in predicting the emergencies using environmental monitoring systems.

Keywords: complex technical systems, engineering-within-nature complex systems, nature & engineering complex systems, environmental monitoring, forecasting emergencies, statistical research, decision support.

Introduction. The complexity of modern technical systems and the increase of man-made risks arising from environmental pollution requires not only the increased reliability of such systems, which can be achieved, in particular, by the use of advanced monitoring and diagnostics, but also by the availability of effective means to predict probable accidents that can occur in the operation of these systems as well as the availability of timely and optimal measures of response to the emergencies. The purpose of establishing the permanent system to monitor the faults occurrence lies in reducing the possibility of sudden unexpected events, undermining the economy of the industrial enterprise, dangerous production stops, damage to equipment and accidents to personnel, as well as to facilitate technical maintenance of equipment. Critical levels of environmental pollution should also be minimized. Although the pursuit of greater reliability and less cost may seem incompatible at first, a closer examination of this issue shows that this is not the case [1].

In Ukraine, a national methodology has been approved to predict the effects of chemical pollution on the environment [2]. In addition, in the areas where environmentally hazardous enterprises are located, specific engineering within nature complex systems are formed, which are characterized by certain trends of environmental changes, which sometimes lead to negative ecological and economic consequences. The material costs of restoring the natural equilibrium within such territories are usually extremely high. Therefore, the problem of creating adequate modeling techniques and forecasting the functioning of industrial enterprises to prevent accidents on them is a matter of first and foremost importance.

The review of existing approaches to forecasting the man-made (anthropogenic) risks. Predicting the state (condition) of the environment under the influence of dangerous man-made objects is becoming increasingly important when solving environmental problems associated with finding optimal forms of environmental safety management [3]. The most characteristic of the following tasks are the following:

- environmental monitoring;
- nature exploitation rationing;
- industrial sites environmental impact assessment.

One of the traditional approaches to predicting anthropogenic impact on the environment is the use of mathematical models that describe the processes and phenomena, which characteristic for the studied natural object [4]. The following methods are most often used in predicting the state of the environment:

- dynamic systems;
- time series (regressions);
- Markov models.

In mathematical modeling, let a natural object (water object, soil, stand, atmospheric air, etc.) be considered as a dynamic system containing n components. In this case, the mathematical model of a natural object usually takes the form of a system of differential equations [5].

$$dY_i / dt = g_i(Y_1, ..., Y_n, V_1, ..., V_m, t),$$

where $Y = (Y_1, ..., Y_n)$ is the vector that characterizes the state of the natural object; $V = (V_1, ..., V_m)$ - vector of external factors that affect the state of a natural object; t - time. The solution of the differential equation system is the functional dependencies $Y_i = Y_i(t)$ that allows predicting the state of a natural object.

In the absence of an adequate deterministic dynamic model, statistical forecasting methods are used. Among the statistical methods, the most common method for solving the environmental forecasting problem is regression analysis [6].

Suppose that an observation y_i is the sum of a regular deterministic component and random interferences:

$$y_i = f_i(x_i, \alpha) + \varepsilon_i, \tag{1}$$

where $i = 1..N$ is the observation number; $x_i = (x_{i1}, x_{i2}, ..., x_{ik})$ vector of input factors; f_i - regression function; α - unknown, generally multidimensional parameter, $\alpha \in \mathbb{R}^m$, $m \le N$; ε_i – interferences (random variables) that have zero mathematical expectation, finite variance, and do not correlate with one another. Equation (1) is called the nonlinear regression model. The task is to evaluate an unknown parameter α. As a method of estimation, the least squares method (LSM) is usually used, which leads to the optimization task $\sum_{i=1}^{N} \left(y_i - f_i(x_i, \alpha)\right)^2 \to \min$. In this case, the value α that is the solution to this task is called an estimate under LSM.

The selected model is compared with the original data to check how accurately it describes the time series. A model is considered acceptable if the residuals are small and have a normal distribution.

Another statistical approach for modeling the behavior of these systems is based on stochastic modeling. Stochastic modeling does not use rigorous ratios, but expert and empirical evaluations and a universal mathematical apparatus. Stochastic modeling based on Markov finite-chain theory [7] has been successfully applied in various industries [8].

Suppose that the evolution of an ecosystem is described by the Markov chain. The transitions of the system from one state to another mean the moving a point that depicts the current state of the system from one set of phase space to another, and the corresponding system of phase space sets $A_j, j = 1..m$ is built on the basis of environmental standards. The transition probabilities matrix $P_{ij} = P\left\{\xi_{k+1} \in A_j / \xi_k \in A_i\right\}$, constructed on statistical information, where ξ_k is the vector of system state on the time t_k, ξ_{k+1} is the same vector at time t_{k+1}. Such a description allows you to solve at least three of the following tasks:

1. To determine system transition probabilities $P_{ij}^{(n)}$ from the state A_i to the state A_j in n steps.

2. To find the vector of probabilities $P^{(n)}(B)$ of the system being in all possible states of the set B in n steps, if the state of the system is known at the initial moment.
3. For the specific states of the system, to determine the probabilities of getting into them in no more than n steps and stationary probabilities, which allow to determine the measure (portion) of time that the system is in these states.

The main disadvantage of existing forecasting methods is the inability to estimate the average residence time of a system in one or another set of states and the lack of attention to economic effect of its evolution.

Formulation of the task to model the behavior of engineering-within-nature complex systems. The models based on Markov finite chains have the following characteristics:

- simplicity of the content;
- actual environmental standards and regulations are naturally taken into account, since the phase space is built on the basis of current environmental legislation;
- the possibility of reducing the set of estimated parameters to the elements of the transition matrix.

It should also be noted that the use of such an interpretation of the system evolutions eliminates the need to determine the distributions of random variables and processes that determine the state of the system.

The practical application of such models, due to the existing advanced theory of Markov chains allows us to use the following criteria of optimality:

- to minimize the probabilities of system states, which are extraordinary situations, in the steady state distribution of the respective chain;
- to maximize the average time of reaching the respective state;
- to minimize the damage caused by the system being in "ecologically disadvantaged" states;
- to maximize the economic impact of the system's operation, taking into account both profits from industrial sites, positive social shifts as well as losses related to environmental damages.

The purpose of this work is to develop a methodology for predicting the occurrence of ecological threats, to study the distribution of time spent by the engineering-within-nature complex system in safe and in unfavorable (unsafe) states, ecological and economic analysis of the consequences of its evolution.

Methods of forecasting and optimizing the economic effect on a discrete set of strategies. Let the system is responsible to control the territories, which represent an amalgamation of zones (regions) that will in future be considered as non-intersecting. The ecosystem phase space Ω is a direct product of Ω_l, where Ω_l is the set of all possible ordered sets of concentrations of harmful substances in the air and water environments of the l-th region of controlled area. The model of each of these zones is a corresponding Markov chain [9]. The natural modification (version) of the Markov property for the situation under consideration is the following:

$$P(T_j \in A_k / T_1 \in A^{(1)},...,T_m \in A^{(m)}) = P(T_j \in A_k / T_{j1}^{(1)} \in A^{(j1)},...,T_{jr}^{(r)} \in A^{(jr)})$$

that is, the probability of finding the j-th zone in the k-th state A_k is determined by the states $A^{(j1)},...,A^{(jr)}$, in which the adjacent zones $T_{j1}^{(1)},...,T_{jr}^{(r)}$ locate. Accordingly, statistical studies of the transition probabilities [10] for each zone should include a study of their dependencies on the "configuration" of the environmental situation in the adjacent zones. Note that in some cases there is even a deterministic dependence between the states of adjacent zones with a certain time lag. This is the case, for example, for the condition of air basins in the case of steady air currents, for water basins of zones settled sequentially downstream. Thus, the happening of an emergency even in one region (or vice versa, the normalization of the ecological situation in it) requires a consistent recalculation of transition probability matrices for the entire controlled area. It should be noted that such calculations often lead to controversial results (we obtain different transition matrices for the same region). To eliminate these contradictions, it is suggested that:

- to create, on the basis of statistical studies, a bank of scenarios that may occur in each zone;
- calculate time lags for interregional effects for each scenario;
- operational management shall be carried out by using standard scenarios with simultaneous control of their adequacy to the real situation.

It should be noted, that the forms of interdependence between transition matrices for adjacent zones can be calculated in two ways:

- based on available statistics;
- on the basis of a correspondence model [11], based on the available information about air currents, dynamics of water reservoirs, etc.

This requires:

- the previous choice of the most likely way of forming such a dependency related to the accumulated information;
- statistical control of incoming information in terms of selecting the most likely hypothesis according to its available dynamics.

The first question to be solved when using this model is the question of discreteness or continuity of time (in the evolution of a chain). The choice of Markov chains with discrete time is explained by not only available practical experience of using them [9], but also to the objectively available periodicity of information inflow into the control system from its primary links.

For discrete-time chains, the problem of homogeneity arises. Homogeneous chains are much easier to investigate, but applying them requires a solid statistical justification, which is not always possible. At the same time, it is natural to use several homogeneous models adapted to the operating modes of the enterprises and the seasons. Thus, one task of considering inhomogeneous chains can be replaced by several tasks of analyzing the corresponding homogeneous chains and developing an algorithm of transition from one of them to another depending on the current state.

The next question is the choice of the phase space structure (set of states) of the chain (Fig. 1). Its solution is based on a legislative base (framework) that determines the levels of environmental pollution and the need to consider such levels for each of the regions that form the controlled system. At the same time, phase space, constructed as a direct product of "local" phase spaces, which in turn duplicate the levels of pollution in the respective zones, is, on the one hand, too cumbersome (in the presence of m regulated levels of pollution and n zones it contains m^n states) and, at the same time, is not always adequate from the point of view of the system description, since it does not contain clearly identified states of "threatening". From this point of view, it is advisable to isolate "transient" states in some zones, which would mean the approaching to the critical levels of pollution, or vice versa - the tendency to decrease them. At the same time, based on economic (potential loss) and other considerations, the primary phase space containing $(m^*)^n$ (m^* - the number of levels of contamination, taking into account the abovementioned additional) phase space should be enlarged (i.e. to combine several states into one).

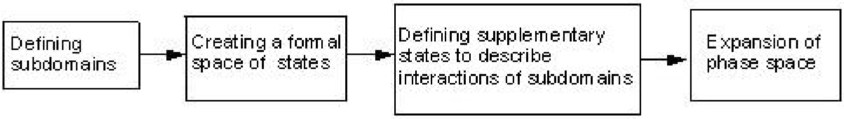

Fig. 1. Building a graph of the system states

After the final formation of the phase space (which may be different under the solving the problems of economic, ecological, political, social, technological and other directions) and determine the corresponding transition matrix, one can classify its states (Fig. 2).

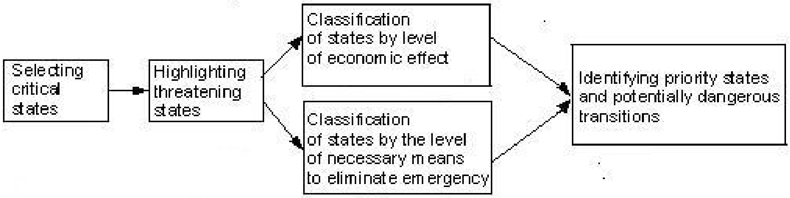

Fig. 2. Defining the basic characteristics of the system states

The opportunity of decomposing the phase space into classes of achievability, that is constructing the states graph of the chain (Fig. 3), requires in-depth analysis. By providing a high probability of defining the "starting" state of the system, it is possible to limit yourself to a chain that is non-decomposable.

Formal (mathematical) distribution of absorbing states of the system should be consistent with their character as states of ecological catastrophe resulting from the limited resources of natural environmental purification. For such states, they determine the average time to achieve them and the probability of achieving them no earlier than a fixed time. If in this case for a random time τ of achieving of one of such states we have $M[\tau] < \tau_0$, or for the probability p^* of getting to such a state not earlier than a certain time, an inequality $p^* < p_0$ is true, where τ_0, p_0 pre-set values, the system is considered as highly-insecure and needs structural changes (Fig. 4).

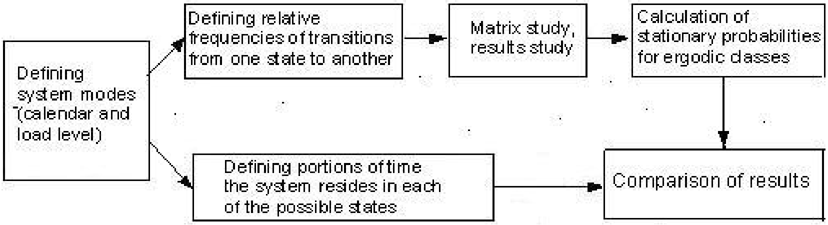

Fig. 3. Finding the transient probabilities of the Markov chain for non-critical states

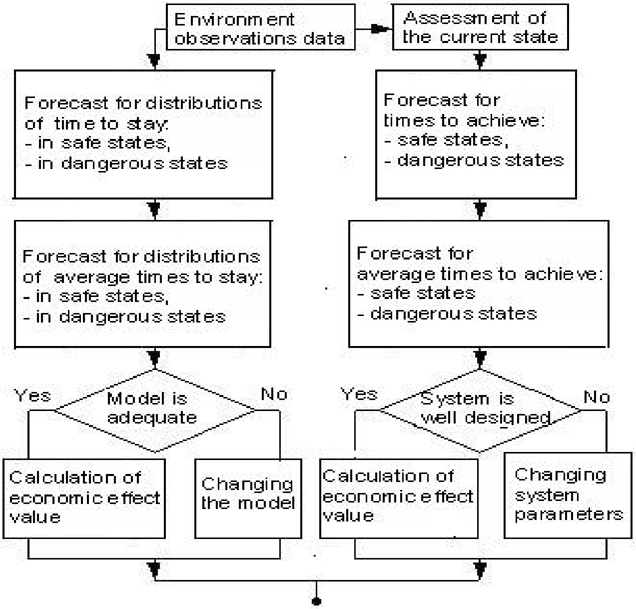

Fig. 4. Pattern cycle of checking the model adequacy and system quality

For each of the other states of the chain, along with its probabilistic characteristics, environmental and economic parameters are also considered: achievable economic effect, permissibility of the corresponding environmental pollution, possibility of exploitation of natural resources and technological objects. This allows not only to set the "rating" of the states of the system from the most desirable to the extremely undesirable, but also to set optimization tasks for it, based on the possibilities of choosing the initial state and influencing the matrix of transient probabilities [10]. Given the real characteristics of the system under consideration, it is proposed to use Markov periodic chains to model its behavior [12], which gives an additional opportunity to characterize and detect emergencies as a "deviation from periodicity" in the behavior of the system.

Another feature of the proposed methodology is the optimization of a discrete set of strategies based on a set of scenarios, which allows to avoid purely mathematical problems in solving extreme (and in some cases variational) tasks due to the really existing system of industrial installations (machinery) operating modes.

The paper proposes a methodology that allows to combine economic estimates with the ability to predict the situation and optimize decision making to improve the environmental situation in areas potentially exposed to chemical pollution.

The stages of implementation of the methodology are as follows:

1. By using available transition matrices for the chains that describe the environmental situation in the zones, they identify such modes of operation of technological systems that, during a predetermined period (no more than N transitions), can lead to situations that are classified as extremely dangerous, in at least one of the regions.
2. For situations that are considered unfavorable, a mode of operation is selected in which the weighted sum of the probabilities of their achieving (attaining) is minimized by no more than M transitions or stationary probabilities of these states for a particular chain. The coefficients in such a weighted sum shall be chosen on the basis of the need to ensure that the expected average level of contamination for each of its components is properly restrained:

$$\begin{cases} \alpha_{11}\cdot p_1+...+\alpha_{1l}\cdot p_l\le s_1 \\ ... \\ \alpha_{k1}\cdot p_1+...+\alpha_{kl}\cdot p_l\le s_k \end{cases}.$$

3. After performing the previous steps for each of the zones, the optimization is performed, according to the criterion of the maximum distance of the system from the dangerous level of contamination, i.e. choosing such mode of its operation, under which

$$T=ET(f_1,...,f_n)\to\max,$$

where $T(f_1,...,f_n)$ is the time for the value $A_1\cdot f_1+...+A_n f_n$ to reach the critical level F, $f_1,...,f_n$ – the characteristics of the industrial pollution of the zones, $A_1,...,A_n$ – the weighting coefficients.

4. If the previous task is solved, but there are a number of strategies, when applied, haven't provided the results almost indistinguishable from the optimal one, then for these strategies they shall calculate: a) the average amount of harm from the system being in environmentally hazardous states; b) the average economic effect of the system operation, taking into account both profits from the operation of industry, positive socio-economic shifts, as well as the losses described above. It is clear that comparing the outcome of choosing one of the strategies, in this case, is necessary for decision making at the government level.

The control of the system can be carried out both by changing the phase space (revision of norms and levels of pollution) and by changing the matrix of transient probabilities, both of which can be combined in series. It should be noted that changing the transition probability matrix can require significant investment (e.g., improved reliability of industrial installations, reduced emissions levels, etc.), which should be taken into account when making appropriate management decisions.

Conclusions. The article proposes a technique for forecasting emergencies that may occur when a nature & engineering complex system operates. The use of the methodology presented above will allow to increase the efficiency of functioning of enterprises, generate the balanced informed management decisions and to create software and technologies to respond the emergencies.

REFERENCES

1. *Himmelblau D.* Detection and diagnosis of malfunctions in chemical and petrochemical processes/D.Himmelblau; per. from English–L-.:Chemistry,1983.-352p.
2. The methodology for predicting the availability of viliva (Wikidu) of non-secure chemical speeches in case of accidents at industrial sites and transport [Electronic resource]. - Access mode: http://zakon4.rada.gov.ua/laws/show/z0326-01
3. *Pankratova N.D.* Recognition of an emergency in the dynamics of the operation of a technologically dangerous object /N.D.Pankratova, A.M.Raduk//Scientific news NTUU «KPU». -2008.-No.3.-P.43–52.
4. *Getun G.V.* Differential processes with cumulative characteristics during operation / Getun G.V., Butsenko Yu.P., Balina O.I., Bezklubenko I.S., Solomin A.V. // Optical materials and theory equipment. - 2019.No102. - P.243-252.
5. *Malinetskii G.G.* Modern problems of nonlinear dynamics / G. G. Malinetskii, A. B. Potapov. - M.: Editorial URSS, 2000.-336 p.
6. *Demidenko E.Z.* Optimization and regression / E.Z. Demidenko. -M.:Nauka,1989.-296p.
7. *Li Ts*. Estimation of parameters of Markov models by aggregated time series / Ts. Li, D. Judge, A. Zelner; per. from English - M.: Statistics, 1977.- 221 p.
8. *Bardin I.V.* Prediction of situations and optimization of decision-making on improving the environmental situation in areas with oil pollution based on finite Markov chains / I.V. Bardin, Yu. D. Motorygin, M.A. Galishev // Problems of risk management in the technosphere . - 2009. - No. 1–2. - p. 17–23.
9. *Admaev O.V.* Use of Markov processes for assessing the environmental safety of an airspace of a city / O.V. Admaev, T.V. Gavrilenko // Optics of the atmosphere and ocean. - 2010. - T. 23, No. 12. - p. 1087-1090.
10. Karmanov A.V. Research of controlled finite Markov chains with incomplete information (minimax approach) / V.A. Karmanov. - M.: Fizmatlit, 2002. - 176 p.
11. *Khabarov V. I.* Markov model of transport correspondence / V.I. Khabarov, D.O. Molodtsov, S.G. Khomyakov // Reports of TUSUR. - 2012. - No. 1 (25), part 1. - p. 113–117.
12. *Priymak, M.V.* Periodic Markov Lanterns in the tasks of statistical analysis and forecasting energy supply / M.V. Priymak // Technical electrodynamics. - 2004. - No. 2. - P. 3–7.

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SITUATION FORECASTING AND DECISION-MAKING OPTIMIZATION BASED ON USING MARKOV FINITE CHAINS FOR AREAS WITH INDUSTRIAL POLLUTIONS

The paper considers the issues of predicting the situations and optimizing decision-making to improve the environmental situations in the areas with industrial pollution based on the finite Markov's chains.

The article systematizes the existing approaches to forecasting technological risks. The problems associated with the search for optimal forms of environmental safety management and approaches for predicting anthropogenic impact on the environment using mathematical models are considered. To predict the state of the environment, stochastic modeling is proposed, the basis of which is the theory of finite Markov chains. A technique for predicting and optimizing the economic effect on a discrete set of strategies has been developed. The figures show: building system states graph, determining the basic characteristics of system states, finding transition probabilities of Markov chains for non-critical states, a typical cycle of checking the model's adequacy and system quality.

Based on the analysis of existing approaches to forecasting technological risks, a methodology has been developed for forecasting and optimizing the economic effect on a discrete set of strategies. The proposed methodology allows combining economic estimates with the ability to predict the situations and optimize decision-making to improve the environmental situation in the areas of possible chemical pollution.

Using the developed methodology will increase the efficiency of the industrial enterprises, facilitate generating informed management decisions, create software and hardware ways to respond the emergencies.

The methodology for modeling engineering within nature complex systems and the optimization of decision-making based on finite Markov chains in the areas with industrial pollution will be helpful to researchers and operators of complex technical systems in predicting emergencies using environmental monitoring systems.

Keywords: complex technical systems, engineering-within-nature complex systems, nature & engineering complex systems, environmental monitoring, emergency forecasting, statistical research, decision support.

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Гетун Г., Буценко Ю., Лабжинський В., Баліна О., Безклубенко І., Соломін А. **Прогнозування ситуації та оптимізація прийняття рішень на основі використання кінцевих ланцюжків Маркова для районів з промисловими забрудненнями** // Опір матеріалів та теорія споруд: Наук.-техн. збірник. - К.: КНУБА, 2020. – Вип. 104. - С. 164-174.

У статті пропонується методологія моделювання комплексних систем інженерії (далі, «системи»), яка буде корисною для дослідників та операторів складних технічних систем при прогнозуванні надзвичайних ситуацій за допомогою систем моніторингу навколишнього середовища.

Getun G., Butsenko Y., Labzhinsky V., Balina O., Bezklubenko I., Solomin A. **Situation forecasting and decision-making optimization based on using markov finite chains for areas with industrial pollutions** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – K.: KNUBA, 2020. – Issue 104. – P. 164-174.

The paper proposes a methodology for modeling engineering-within-nature complex systems (further, "systems"), which will be helpful for researchers and operators of complex technical systems in predicting the emergencies using environmental monitoring systems.

Author (academic degree, academic rank, position): Getun Galina Vyacheslavovna, PhD Technical Sciences, Professor of the Architectural Design Department of KNUCA
Working address: 31, Povitriaflotsky Prospekt, Kyiv, Ukraine, 03680, GETUN Galina Vyacheslavivna, Kyiv National University of Construction and Architecture
Working phone +38 (044) 245-44-32
E-mail: GalinaGetun@ukr.net
Cellphone. +38 (067) 320-11-93;
ORCID ID: http://orcid.org/0000-0002-3317-3456

Author (academic degree, academic rank, position): Volodymyr LABZHINSKY , PhD of Technical Sciences, Associate Professor of Energy Processes and Systems Design Automation Department of Igor Sikorsky Kyiv Polytechnic Institute
Working address: 37 Peremohy avenue, Kyiv, Ukraine, 03056, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", LABZHINSKY Volodymyr Anatolyevich
Working phone +38 (044) 236-79-89;
E-mail: sergeant@aprodos.kpi.ua
ORCID ID: https://orcid.org / 0000-0003-0970-770X

Author (academic degree, academic rank, position): Yuriy BUTSENKO, PhD of Physical and Mathematical Sciences, Associate Professor of Mathematical Analysis and Probability Theory the Department of Igor Sikorsky Kyiv Polytechnic Institute
Working address: 37 Peremohy avenue, Kyiv, Ukraine, 03056. National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
Working phone +38 (044) 236-79-89;
Cellphone. +38 (066) 937-83-73;
E-mail: elena.i.balina@gmail.com
ORCID ID: https://orcid.org/0000-0003-4806-9587

Author (academic degree, academic rank, position): BALINA Olena Ivanovna, PhD of Technical Sciences, Associate Professor, Department of ITPPM at KNUCA,
Working address: 31, Povitroflotsky Prospekt, Kyiv, Ukraine 03680, BALINA Olena Ivanivna, Kyiv National University of Construction and Architecture
Working phone +38 (044) 245-04-02;
Cellphone. +38 (066) 937-83-73;
E-mail: elena.i.balina@gmail.com
ORCID ID: https://orcid.org/0000-0001-6925-0794

Author (academic degree, academic rank, position): BESKLUBENKO Irina, PhD of Science (Engineering), Associate Professor, Department of ITPPM KNUCA,
Working address: 31, Povitroflotsky Prospekt, Kyiv, Ukraine, 03680, Bezklubenko Iryna Serhiivna, Kyiv National University of Construction and Architecture
Working phone +38 (044) 245-04-02;
Cellphone. +38 (066) 794-01-84;
E-mail: i.bezklubenko@gmail.com
ORCID ID: https://orcid.org/0000-0002-9149-4178

Author (degree, academic rank, position): Solomin Andriy Vyacheslavovich, PhD of Physical and Mathematical Sciences, Asociate Professor of Biosecurity and Health Igor Sikorsky Kyiv Polytechnic Institute
Working address: 37 Peremohy avenue, Kyiv, Ukraine 03056 National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Andriy Solomin
Working phone +38 (044) 204 85 74;
Mobile phone +38 (050) 927-10-63;
Email: andr-sol@i.ua
ORCID ID: http://orcid.org/0000-0002-5226-8813