UDC 330.46
JEL: E22; O31
DOI: https://doi.org/10.32983/2222-4459-2023-10-162-174

INNOVATION DEVELOPMENT OF AN ENTERPRISE: MODELING DYNAMICS

©2023 MALYARETS L. M., VORONIN A. V., LEBEDEVA I. L., LEBEDIEV S. S.

UDC 330.46
JEL: E22; O31

Malyarets L. M., Voronin A. V., Lebedeva I. L., Lebediev S. S. Innovation Development of an Enterprise: Modeling Dynamics

At the present stage of economic development, the leading role in ensuring the competitiveness of both an singular enterprise and the country as a whole, as well as in creating conditions for the transition to sustainable development, is played by the successful implementation of the latest scientific developments in production processes, comprehensive support for the strategy of innovative development. The development and implementation of innovations is a complex dynamic process that requires the use of special research methods. Such a method is system dynamics, which makes it possible to take into account the nonlinearity of the impact of innovation on the state of the economy. The paper considers the methodology for building a model for managing innovation processes, taking into account the self-organization of the logistic type. The main danger that can accompany the evolution of innovation processes is the emergence of unacceptable dynamic modes, so one of the tasks of the study was to determine the conditions capable of ensuring the stability of equilibrium states of a complex dynamic system according to the proposed models. The object of research is a complex dynamic system, between the elements of which there is both positive and negative feedback. To build a model of the dynamics of innovation processes, the mathematical apparatus of the theory of differential equations was applied, which made it possible to consider the development of the innovation process in continuous time. With the help of the instrumentarium of nonlinear dynamics, a study of the stability of diffusion of innovations depending on the parameters of the control influence was carried out. The conditions for the transition of the system to a critical state, which may be accompanied by the occurrence of bifurcations and chaos, have been determined. Particular attention was paid to determining the structural stability of the regulated innovation process in the case when both equilibrium positions are close in terms of parameter values. It is expedient to apply the proposed model to solve the problem of innovation management both at the State level and at the level of an individual industry or an individual enterprise. The obtained theoretical conclusions were confirmed through the use of simulation modeling.

Keywords: *system approach, nonlinear dynamics, feedback, phase space, qualitative analysis by trajectories, order parameters, bifurcations.*
Fig.: *5.* ***Formulae:*** *35.* ***Bibl.:*** *27.*

Malyarets Lyudmyla M. *– D. Sc. (Economics), Professor, Head of the Department of Mathematics and Mathematical Methods in Economics, Simon Kuznets Kharkiv National University of Economics (9a Nauky Ave., Kharkiv, 61166, Ukraine)*
E-mail: *malyarets@ukr.net*
ORCID: *https://orcid.org/0000-0002-1684-9805*
Researcher ID: *https://www.webofscience.com/wos/author/record/T-9858-2018*
Scopus Author ID: *https://www.scopus.com/authid/detail.uri?authorId=57189248374*

Voronin Anatolii V. *– PhD (Engineering), Associate Professor, Associate Professor of the Department of Mathematics and Mathematical Methods in Economics, Simon Kuznets Kharkiv National University of Economics (9a Nauky Ave., Kharkiv, 61166, Ukraine)*
E-mail: *voronin61@ ukr.net*
ORCID: *https://orcid.org/0000-0003-2570-0508*

Lebedeva Irina L. *– PhD (Physics and Mathematics), Associate Professor, Associate Professor of the Department of Mathematics and Mathematical Methods in Economics, Simon Kuznets Kharkiv National University of Economics (9a Nauky Ave., Kharkiv, 61166, Ukraine)*
E-mail: *irina.lebedeva@hneu.net*
ORCID: *https://orcid.org/0000-0002-0381-649X*

Lebediev Stepan S. *– Senior Lecturer of the Department of Mathematics and Mathematical Methods in Economics, Simon Kuznets Kharkiv National University of Economics (9a Nauky Ave., Kharkiv, 61166, Ukraine)*
E-mail: *stepan.lebedev@hneu.net*
ORCID: *https://orcid.org/0000-0001-9617-7481*

УДК 330.46
JEL: E22; O31

Маляренць Л. М., Воронін А. В., Лєбєдєва І. Л., Лебедєв С. С. Моделювання динаміки інноваційного розвитку підприємства

На сучасному етапі розвитку економіки провідну роль у забезпеченні конкурентоспроможності як окремого підприємства, так і країни загалом, а також у створенні умов для переходу до сталого розвитку відіграє успішність запровадження у виробничих процесах новітніх наукових розробок, всебічна підтримка стратегії інноваційного розвитку. Розробка та впровадження інновацій є складним динамічним процесом, який потребує застосування спеціальних методів дослідження. Таким методом є системна динаміка, що дає можливість враховувати нелінійність самого процесу впровадження інновацій. У роботі розглядається методологія побудови моделі управління інноваційними процесами з урахуванням самоорганізації логістичного типу. Основною небезпекою, яка може супроводжувати еволюцію інноваційних процесів, є поява неприйнятних динамічних режимів, тому однією із завдань дослідження було визначення умов, здатних згідно із запропонованими моделями забезпечити стійкість рівноважних станів складної динамічної системи. Об'єктом дослідження є складна динамічна система, між елементами якої існує як позитивний, так і негативний зворотний зв'язок. Для побудови моделі динаміки інноваційних процесів було застосовано математичний апарат теорії диференційних рівнянь, що дозволяло розглядати розвиток інноваційного процесу в неперервному часі. За допомогою інструментарію нелінійної динаміки проведено дослідження стійкості дифузії інновацій залежно від параметрів керівного впливу. Визначено умови переходу системи у критичний стан, який може супроводжуватися виникненням біфуркацій і хаосу. Особливу увагу було приділено визначенню структурної стійкості регульованого інноваційного процесу у випадку, коли обидва положення рівноваги є близькими за значеннями параметрів. Запропоновану модель доцільно застосовувати для розв'язання проблеми управління інноваційними процесами як на державному рівні, так і на рівні окремої галузі чи окремого підприємства. Отримані теоретичні висновки були підтверджені завдяки використанню імітаційного моделювання.

***Ключові слова:** системний підхід, нелінійна динаміка, зворотний зв'язок, фазовій простір, якісний аналіз за траєкторіями, параметри порядку, біфуркації.*
***Рис.:** 5. **Формул:** 35. **Бібл.:** 27.*
***Малярець Людмила Михайлівна** – доктор економічних наук, професор, завідувачка кафедри вищої математики та економіко-математичних методів, Харківський національний економічний університет імені Семена Кузнеця (просп. Науки, 9а, Харків, 61166, Україна)*
***E-mail:** malyarets@ukr.net*
***ORCID:** https://orcid.org/0000-0002-1684-9805*
***Researcher ID:** https://www.webofscience.com/wos/author/record/T-9858-2018*
***Scopus Author ID:** https://www.scopus.com/authid/detail.uri?authorId=57189248374*
***Воронін Анатолій Віталійович** – кандидат технічних наук, доцент, доцент кафедри вищої математики та економіко-математичних методів, Харківський національний економічний університет імені Семена Кузнеця (просп. Науки, 9а, Харків, 61166, Україна)*
***E-mail:** voronin61@ ukr.net*
***ORCID:** https://orcid.org/0000-0003-2570-0508*
***Лєбєдєва Ірина Леонідівна** – кандидат фізико-математичних наук, доцент, доцент кафедри вищої математики та економіко-математичних методів, Харківський національний економічний університет імені Семена Кузнеця (просп. Науки, 9а, Харків, 61166, Україна)*
***E-mail:** irina.lebedeva@hneu.net*
***ORCID:** https://orcid.org/0000-0002-0381-649X*
***Лебедєв Степан Сергович** – старший викладач кафедри вищої математики та економіко-математичних методів, Харківський національний економічний університет імені Семена Кузнеця (просп. Науки, 9а, Харків, 61166, Україна)*
***E-mail:** stepan.lebedev@hneu.net*
***ORCID:** https://orcid.org/0000-0001-9617-7481*

The current stage of economic development is defined as the knowledge economy. Under these conditions, the competitiveness of the country is determined by its human potential, which, in particular, is embodied in innovative developments. Problems related to ensuring innovative development not only of an individual enterprise or a certain industry, but also of the country's economy as a whole, attract close attention of both managers of all levels and scientists.

In general, the most effective instrument for solving theoretical problems, as well as analyzing the behavior of complex systems when external conditions change, and predicting their development over time, is mathematical modeling. One of the modern trends in the development of mathematics, expedient to use in the study of systems of different nature and different levels of complexity, is system dynamics. This research method was developed by Jay Forrester back in 1961 and since then has been successfully used to solve problems that arise in complex economic, social, and ecological systems during their life cycle. The use of such models allows improving the management of complex systems. As a mathematical apparatus of system dynamics, the use of differential or difference equations is proposed, providing the possibility of studying the processes that determine the development of the system in continuous or discrete time. At this, the general theory of systems allows us to consider the interaction of interconnected elements of the system, taking into account both positive and negative feedback [1]. It is the presence of feedback that ensures the implementation of a certain degree of self-correction, therefore the system can develop in a given direction. The advantage of the system dynamics method is that it allows not only to create conceptual models, but also to make the transition to simulation models of the «stocks – flows» type [2]. System dynamics provides a general methodological framework that can be applied wherever it is necessary to understand how a complex system changes over time and, accordingly, to influence the direction and speed of these changes. It should also be noted that, in a more general sense, system dynamics is not only a tool for analyzing and further synthesizing ideas about the functioning of the system and its development, but also, as its founder Jay Forrester specifies, a tool for thinking, a philosophy of research.

One of the areas where it is expedient to use the methods of system dynamics as a research tool is innovative development, the implementation of which, as a rule, takes place in several stages and is associated with certain risks. Regardless of whether this process is implemented at the level of an individual enterprise, industry, country, or even the world economy, it is subject to general regularities that are associated with its wave-like nature. Precisely because innovative development is cyclical in nature, it is necessary to build nonlinear models when studying it. The use of nonlinear dynamics makes it possible to take into account the peculiarities of the processes that determine the implementation of innovations, and to make founded managerial decisions to ensure their efficiency.

LITERATURE REVIEW AND PROBLEM STATEMENT

A large number of scientific and practical studies are devoted to the problem of uneven innovative development of economic objects. An example of the nonlinearity of the development of economic objects in the global

The Fundamental, State Budget-Funded Research Work «Ensuring the Innovative Development of Export-Import Activities of Economic Entities in the Public Sector of the Economy under the Martial Law and in the Post-War Conditions». State Registration No. 0123U102012.

sense can be considered long cycles (Kondratiev waves), that are determining the cyclical nature of the development of the world economy. Today, the most grounded explanation of this process is considered to be the conception of technological innovation, the foundations of which were laid by Kondratiev in the middle of the twentieth century and developed thanks to the work of other scholars [3–5 and others]. According to this conception, the ascending phase of the long cycle wave (economic growth) is the result of the development and implementation of the fundamentally new interconnected technologies that have an impact on almost all sectors of the economy, that is, a technical revolution is taking place. The implementation of these novel technologies can significantly reduce production costs and increase profits, that accordingly stimulates business to implement innovation even more widely. It is clear that this process takes place in the presence of the necessary resources. In turn, the diffusion of innovations provides a significant increase in profits, generating additional investments in the development of production. Gradually, the process slows down, and the inflection point is the moment when there is a significant weakening of the effects that initiated the upward phase of the long cycle wave. This leads to a decrease in profits and the business structures lose interest in further novations, so the phase of slowdown in production is replaced by a phase of stagnation or even recession, that can last quite a long time. However, during this phase, there is a gradual accumulation of new progressive technologies, and a new rise is possible only when, taken together, these novel technologies create an opportunity for innovative transformations of production at a new turn of the development spiral. In its simplest form, such a model of evolution can be represented by an S-shaped curve, that corresponds to a logistic function. The world economy has already gone through five long waves in its development, and now humanity is at the beginning of the sixth wave, that will be associated with solving the problem of resource saving [6], and with the introduction of artificial intelligence in various fields of activity [7]. In particular, one of the innovative technologies, the use of which is becoming more and more widespread in various industries, is «green energy» [8].

Similar phases, but on a smaller scale and, accordingly, of shorter duration, are observed in the implementation of innovations at the level of a particular industry or an individual enterprise. But even when the analysis is carried out at the enterprise level, it is advisable to apply a system approach, since in modern conditions innovations acquire a systemic character, since their implementation involves the use of a whole range of technologies and services. In this regard, the concept of an innovation ecosystem has even been formed [9], to describe the environment in which the interaction of innovations of different levels, though aimed at solving a single problem, is carried out. The concept of «ecosystem» is borrowed from biology and defines a business ecosystem as an economic community that unites firms, organizations and individuals, that are considered as «organisms» of the business world [10; 11 and others]. The economic ecosystem has inherent adaptive properties. As for the biological ecosystem, the result of the interaction of the actors of the innovation ecosystem may be its self-organization at certain stages of its active life. The authors of the paper [12] believe that innovation ecosystems should be considered as complex adaptive systems that distribute information and other resources among the elements of the system and learn to respond to external influences. The general principles of construction and elements of the structure of dynamic models used to analyze the diffusion of innovations as the development of a complex system are provided in the paper, referred to as [13]. The referred paper also presents the basic terminology that is used to determine managerial decisions in these models.

It should be noted that the nonlinear nature of feedbacks in a system can cause the emergence of a whole hierarchy of unstable states, which in the process of development of this system can lead to the appearance of boundary cycles, homoclinic structures, and even chaos [14]. Therefore, in order to evaluate the possible trajectories of the system development in phase space, it is expedient to use the mathematical apparatus of nonlinear dynamics as a research method.

It is possible to distinguish four major aspects of innovative development, when considering which it is necessary to take into account the nonlinearity of the dynamics of the system [15]. These are research and development policies, innovation policies, science and technology policies, and regional agglomeration policies. Most research examines assumptions, hypotheses, and policies at a conceptual level, that can be described as exploratory modeling tools. A system approach to modeling innovative development has already been successfully used to analyze processes at the level of individual industries. Thus, in the paper [16] an econometric model has been developed, that allows assessing the effectiveness of the introduction of innovative technologies for transport enterprises, and the presence of a close correlation between the level of innovative technologies and the financial stability of enterprise in the conditions of inconstancy of the external environment is shown. The study [17] is aimed at determining the current state and forecasting the possibilities of applying the system dynamics method in construction projects. In the article [18], the mathematical model of dynamics is considered as the basis for solving problems in the field of suburban and urban transport through investments in improving its infrastructure.

The authors of the paper [19] pay attention to the construction of a model, which can serve as a basis for making a crediting decision on investments in the development of an agricultural enterprise, depending on the capacity of the market under conditions of prices instability. The method of system dynamics is also used to model the behavior of actors involved in the implementation of innovations [20]. In every project participated by a team there is a conflict of interests, that manifests itself in the form of a conflict of ideas, a conflict of existing resources, and even a personal conflict. One way to overcome conflict is to use specific mathematical models of system dynamics.

However, few researchers consider this problem at the theoretical level, that is, at the level of qualitative analysis of the states of the system along phase trajectories. Therefore, the presented study is relevant.

PURPOSE AND OBJECTIVES OF THE STUDY

In order to take advantage of many new technologies, companies need business models that operate at the intersection of different global industries. The purpose of this work is to synthesize a mathematical model focused on the description of innovative processes using the control mechanism in both linear and nonlinear forms. To prevent the occurrence of unacceptable dynamic modes of evolution of innovation processes, the basic tasks of the study are to determine the stability conditions of the equilibrium states of the system in accordance with the proposed models.

MATERIALS AND METHODS

To build a model of innovation dynamics, a system approach is applied using the mathematical apparatus of the theory of differential equations, that allow describing the diffusion of innovations in continuous time. When constructing a model of dynamics, the presence of both positive and negative feedbacks in the system, which have a nonlinear nature, was taken into account. In this regard, the methodology of qualitative analysis of the theory of nonlinear dynamical systems is used in the work, namely, the main attention is paid to identifying trends in the development of the system, new qualities of its behavior. Accordingly, the use of this methodology made it possible to predict the development of the studied innovative processes along trajectories in phase space. Furthermore, the applied mathematical apparatus includes the theory of stability of systems of differential and integral-differential equations with the elements of the theory of bifurcations. To illustrate the qualitative study of the system development, model calculations were carried out by means of the Octave software environment. In these calculations, the parameters of the system of differential equations were selected in such a way that it was possible to visually demonstrate the behavior of the system under study when its state deviates from the equilibrium position.

RESULTS AND DISCUSSION

The logistic curve, allowing to describe the effect of the implementation of innovations in the simplest form, can be determined by the usual differential equation of the first order [21]:

$$\frac{dx}{dt} = \gamma(x - l_L)(l_U - x), \quad (1)$$

where t is the parameter that characterizes the time spent on the development of a new technology;

$x = x(t)$ is the technologically and economically significant indicator, that changes due to the introduction of the innovative technology under consideration, therefore, it characterizes the result of the innovation process;

$\gamma(\gamma > 0)$ – denotes the scale parameter, the inverse of which is the characteristic time of the transition process for the system in which the innovation is introduced;

l_L, l_U – are, respectively, the lower and upper bounds that limit possible changes in the significant indicator x as a result of the implementation of innovative technology. At this, l_L corresponds to the value of the indicator x at the stage when the introduction of innovations is initiated, and l_U corresponds to the maximum value of the indicator x, that can be achieved through the effective use of the innovative technology under consideration.

As the costs incurred for the introduction of a new technology increase, the significant technological (or economic) indicator cannot decrease, therefore, ideally, the function $x = x(t)$ is a monotonically increasing one. Moreover, such growth is characterized by an increase in the growth rate of the indicator x at the initial stage (near the lower limit l_L) and an inhibition of growth at a later stage when the significant indicator approaches its upper limit l_U, in other words, when the process reaches saturation. That is, the graph of changes in a significant indicator over time is an S-shaped (logistic) curve. The differential equation (1) can be considered as a formalization of the law of transition of quantitative changes into qualitative ones in relation to cumulative processes in the economy, that are associated with the implementation of novel technologies even at an individual enterprise or in a certain industry. When the diffusion of innovations takes place simultaneously in several leading sectors of the economy, then we are talking about a technical revolution. It is the current stage of development of innovation processes that is considered as the Fourth industrial revolution, or Industry 4.0 [22]. The impetus for the beginning of the Fourth industrial revolution was the widespread introduction of cyber-physical systems into industry, in particular, into the processing industry of Germany.

The differential equation (1) has a general solution:

$$x(t) = l_L + \frac{(l_U - l_L) \cdot f(t)}{f(t) + k}, \quad (2)$$

where $f(t) = \exp\left((l_U - l_L) \cdot \gamma t\right)$;

k is an arbitrary constant that depends on the initial condition $x(0) = x_0$.

In addition to the general solution, the equation (1) has two other special solutions, namely $x_1^* = l_L$ and $x_2^* = l_U$. These solutions characterize the state of equilibrium of the system, while $x_1^* = l_L$ is an unstable equilibrium (the starting point that corresponds to the beginning of innovation), and $x_2^* = l_U$ is a stable equilibrium (the endpoint that corresponds to the completion of the innovation process).

It should be noted that the equation (2) provides an exhaustive description of the process of self-organization of innovation.

Let's now consider the case when it is necessary to take into account additional factors that affect the speed of implementation of innovations. An example of such factors can be a set of measures for the State regulation of innovation processes. Although the introduction of innovative technologies begins with industry, later it covers all spheres of life. And if the forecasts of development in the industrial sphere are very optimistic, the same cannot be said of the impact of the modern industrial revolution on social life. Researchers even suggest that the implementation of innovative processes may result in social instability in society [23]. Thus, there is a contradiction between the needs of the economy, for the satisfaction of which it is necessary to promote the introduction of innovations in every possible way, and the social needs, which would like the process of diffusion of innovations to occur rather slowly, allowing society to adapt to new conditions. Accordingly, if we consider the diffusion of innovations at the level of an individual enterprise, then the counteraction to this process can be competitive phenomena in the innovation market. However, if we consider the diffusion of innovations at the macro level, then the State regulation of this process also comes into play. So, in general, the process of introducing innovations should be considered as a system with feedback. This feedback can be not only positive, but also negative. And at the macro level, such negative feedback is materialized through government regulation. The *Fig. 1* shows a simplified scheme for managing the processes of diffusion of innovations, that reflects a system approach to its analysis.

Formally, the external control influence can be implemented as feedback in the form of an additional component in the equation (1):

$$\frac{dx}{dt} = \gamma(x - l_L)(l_U - x) + \alpha \cdot \varphi, \quad (3)$$

where $\varphi = \varphi(\tilde{o})$ is a controlling influence, being a nonlinear function of the time spent on the development of a new technology; the coefficient $\alpha = \{-1; 1\}$ characterizes the direction of the control influence, its positive value means that the feedback is positive too, and the negative value corresponds to the negative feedback.

Let's suppose, that the function $\varphi = \varphi(\tilde{o})$ is quadratic in terms of the variable *x*. Let's represent it as:

$$\varphi(x) = \varphi_0 + \varphi_1 x + \varphi_2 x^2, \quad (4)$$

where $\varphi_0, \varphi_1, \varphi_2$ are arbitrary constants, while $\varphi_2 \neq 0$.

Let's suppose, that the feedback in the diffusion system of innovation is negative, i. e.: $\alpha = -1$. We will also assume, that $\gamma = 1$. Then, after substituting the control function in equation (3), we get:

$$\frac{dx}{dt} = -(\varphi_0 + l_L l_U) + (l_L + l_U - \varphi_1)x - (\varphi_2 + 1)x^2. \quad (5)$$

It should be noted that the structure of singular points (equilibrium position) of the differential equation (5) is defined as the solution of the quadratic equation:

$$(\varphi_2 + 1)x^2 - (l_L + l_U - \varphi_1)x + (\varphi_0 + l_L l_U) = 0. \quad (6)$$

We find the discriminant of the equation (6):

$$D = (l_L + l_U - \varphi_1)^2 - 4(\varphi_2 + 1)(\varphi_0 + l_L l_U). \quad (7)$$

If $D > 0$, then there are two equilibrium positions for the equation (5). At $D = 0$ it is possible to have a twofold (single) equilibrium position. If $\varphi_2 + 1 > 0$, a higher value of x_2^* corresponds to a stable equilibrium position, and a lower value of x_1^* corresponds to an unstable position. When the equilibrium positions are close to each other, that is, the difference $x_2^* - x_1^*$ becomes an infinitesimal value (this is realized when $D \to 0$), there is a structural instability of the system, that means, a bifurcation of «saddle-knot» type occurs. To study the topologi-

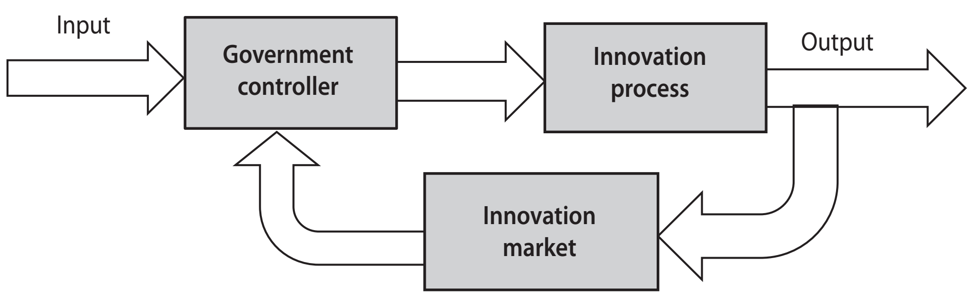

Fig. 1. A general feedback scheme implemented in the process of diffusion of innovations

Source: developed by the authors.

cal properties of this bifurcation, we will make certain transformations.

Let's introduce a new variable $y = y(t)$, with respect to which the significant indicator $x = x(t)$ is a linear function:

$$x(t) = \frac{2y(t) + l_L + l_U - \varphi_1}{2(\varphi_2 + 1)}. \quad \textbf{(8)}$$

As result of the application of the new variable, the differential equation (5) takes the form:

$$\frac{dy}{dt} = a - y, \quad \textbf{(9)}$$

where $a = \frac{\varphi_0 + l_L l_U}{\varphi_2 + 1} - \frac{(\varphi_1 - l_L - l_U)^2}{4(\varphi_2 + 1)^2}$.

That means, $a = -\frac{D}{4(\varphi_2 + 1)^2}$.

The differential equation (7) is a normal form of the local «saddle-knot» bifurcation if the positive parameter a is infinitesimal, i. e., the equation (7) describes the behavior of the model (5) in the small vicinity of the twofold equilibrium position. Thus, at $a \to 0$ there are two equilibrium positions in the system (9), one of which is stable and the other unstable. At $a = 0$ the stable and unstable equilibrium positions meet and combine into a semi-stable singular point, and then annihilate, i. e., a single (twofold) equilibrium state arises, and at $a < 0$ the equilibrium position disappears, and the system can make a sudden transition to a new state that is very different from the previous one. This bifurcation value of the parameter is sometimes referred to as the «fixation point».

Let's take a closer look at the state of stable equilibrium. When the coefficient of the linear regulator φ_1 approaches its critical value at $a = 0$, the area of attraction of this equilibrium position decreases on one side, and after the disappearance of equilibrium, all solutions disappear from the phase region under consideration. In economics, this phenomenon is called «disequilibrium», leading to a catastrophic loss of stability. This type of catastrophe is called «fold-down» [24].

If $\varphi_2 + 1 < 0$, that means, $\varphi_2 < -1$, there is a transcritical bifurcation, or the so-called stability exchange bifurcation. If additional conditions $\varphi_0 = -l_L l_U$ and $\varphi_1 = l_L + l_U$ are imposed, then the differential equation (5) takes the form:

$$\frac{dx}{dt} = -(\varphi_2 + 1)x^2. \quad \textbf{(10)}$$

The differential equation (10) describes a system with a strong positive feedback and can characterize a mode with an exacerbation. The private solution of the equation (11) can be given in the form:

$$x(t) = \frac{x_0}{1 + x_0(\varphi_2 + 1)t}. \quad \textbf{(11)}$$

At the time moment $t^* = -\frac{1}{x_0(\varphi_2 + 1)}$, the value of the significant indicator increases to infinity. Obviously, the solution (11) can exist only until the moment t^* comes, and the very moment of exacerbation of t^* depends on the initial condition $x(0) = x_0$. The higher the value of x_0, the shorter the lifetime of the solution. This means that a certain real process can be described for some time by differential equations, the solution of which increases in the exacerbation mode. In this case, it is impossible to predict the course of the process on the basis of a linear or even more complex interpretation.

Let's return to the original equation (1) and consider another approach to the construction of control influence in a complex system describing the diffusion of innovations. This approach is based on the use of linear control in the conditions of the existence of an aftereffect, that is, taking into account the previous states of the process under study.

We will consider the equation (1) in a form that supports fewer parameters. Let $t = \gamma t_0$, $z = x - l_L$ and $L = l_U - l_L$, then the equation (1) takes the form:

$$\frac{dz}{dt} = z(L - z). \quad \textbf{(12)}$$

Equation (12) has two special solutions, namely $z_1^* = 0$ and $z_2^* = L$. These solutions define the equilibrium points of the system under consideration. At this, as already noted with regard to the special solutions of the original equation (1), the point $z_1^* = 0$ corresponds to the state of unstable equilibrium, and the point $z_2^* = L$ – to the state of stable equilibrium.

Again, let's consider a situation where it is necessary to take into account additional factors that affect the speed of introduction of innovations. Let such a factor, as in the previous example, be a set of the State-controlled measures to regulate innovation activity. The control influence $u = u(z)$, that determines the feedback, is introduced into equation (12) in the form of addition to obtain the following:

$$\frac{dz}{dt} = z(L - z) + \alpha \cdot u, \ \alpha = \{-1; 1\}. \quad \textbf{(13)}$$

Since it is expedient to consider only negative feedback, we will denote the function that characterizes its controlling influence as $u = -kv$. The variable $v = v(t)$ is the output characteristic of a linear regulator with an impulse function $Q(t)$, k is a certain constant coefficient ($k > 0$). Then we have the following general solution of the equation (13):

$$v(t) = \int_{-\infty}^{0} z(t + s) \cdot Q(-s)\, ds, \quad \textbf{(14)}$$

where s – is the integration variable. The choice of such boundaries of integration is explained by the fact that we take into account the control influence that was exercised before the beginning of the process of diffusion of innovations. With regard to the function $Q(t)$, it should be noted that it meets the normalization condition as follows:

$$\int_{-\infty}^{0} Q(-s)ds = 1. \qquad \textbf{(15)}$$

In its simplest form, this function can be represented as a transient function of a first-order aperiodic chain:

$$Q(t) = \omega \cdot e^{-\omega t}, \qquad \textbf{(16)}$$

where ω is a constant value that characterizes the inertia of the control system.

Let's give the relation (13), (14) and (16) in the form of a system of two ordinary differential equations:

$$\begin{cases} \dfrac{dz}{dt} = z(L - z) - kv; \\ \dfrac{dv}{dt} = \omega z - \omega v. \end{cases} \qquad \textbf{(17)}$$

The system (17) has two equilibrium positions, the first of which is implemented $z_1^* = 0;\ v_1^* = 0,$ at and the second at $z_2^* = L - k;\ v_2^* = L - k$ provided that $L > k$.

Let's introduce new variables that contain the sense of deviation from the state of equilibrium $\tilde{z} = z - z^*,\ \tilde{v} = v - v^*.$ In these new variables, the system of differential equations takes the form:

$$\begin{cases} \dfrac{d\tilde{z}}{dt} = (L - 2z^*)\tilde{z} - k\tilde{v} - \tilde{z}^2; \\ \dfrac{d\tilde{v}}{dt} = \omega\tilde{z} - \omega\tilde{v}. \end{cases} \qquad \textbf{(18)}$$

Now we write down the characteristic polynomial, or the spectral equation with respect to the eigenvalues of λ of the matrix of the linear part of the system (18). This equation is:

$$\lambda^2 + (2z^* + \omega - L)\lambda + \omega(k - L + 2z^*) = 0. \qquad \textbf{(19)}$$

In the case of a trivial state of equilibrium for which $z_1^* = 0,$ the quadratic equation (19) takes the form:

$$\lambda^2 + (\omega - L)\lambda + \omega(k - L) = 0. \qquad \textbf{(20)}$$

Since $L > k$, the free member of equation (20) is negative. This means that the trivial state of equilibrium is a «saddle», i. e., it corresponds to an unstable equilibrium.

Let's consider the behavior of the system in the vicinity of the non-negative equilibrium position: $z_2^* = L - k.$ In this case, the spectral equation (19) takes the form:

$$\lambda^2 + (L - \omega - 2k)\lambda + \omega(L - k) = 0. \qquad \textbf{(21)}$$

Let's assume that the coefficients of equation (21) are small quantities. Then the equation (21) can be rewritten in the form:

$$\lambda^2 - \mu_2\lambda - \omega\mu_1 = 0, \qquad \textbf{(22)}$$

where $L - \omega - 2k = -\mu_2$ and $L - k = -\mu_1$.

At $\mu_1 = \mu_2 = 0$ the solution of equation (22) is a twofold zero, and therefore it can be assumed that in the nonlinear system of differential equations (17) the existence of the so-called Bogdanov – Takens bifurcation [24; 26] is possible. For a detailed study of the properties of the «double zero» bifurcation, it is necessary to represent the system (17) in normal form.

Let $\tilde{z} = \omega v_1 + v_2,\ \tilde{v} = \omega v_1.$ Then the system of differential equations (17) after algebraic transformations takes the form:

$$\begin{cases} \dfrac{dv_1}{dt} = v_2; \\ \dfrac{dv_2}{dt} = \omega\mu_1 v_1 + \mu_2 v_2 - \omega^2 v_1^2 - 2\omega v_1 v_2 - v_2^2. \end{cases} \qquad \textbf{(23)}$$

Let's make two more variable replacements in succession. First, let's assume that $v_1 = p_1 - \dfrac{p_1^2}{2};$ $v_1 = p_2 - p_1 p_2.$ Then let's move on to the variables $p_1 = -\dfrac{q_1}{4} - \dfrac{2\mu_1}{\omega^2};\ p_2 = -\dfrac{\omega q_2}{8}$ and $t = \dfrac{2}{\omega}\tau.$ As a result, we will get a normal form for the system (23):

$$\begin{cases} \dfrac{dq_1}{d\tau} = q_2; \\ \dfrac{dq_2}{d\tau} = \beta_1 + \beta_2 q_2 + q_1 q_2 + q_1^2. \end{cases} \qquad \textbf{(24)}$$

Accordingly, $\beta_1 = -\dfrac{4\mu_1^2}{\omega^2};\ \beta_2 = \dfrac{2(\mu_2 - \mu_1)}{\omega}.$

For the system (24), the stationary points are determined by the formula:

$$(q_1^*; q_2^*) = (\pm\sqrt{\beta_1}; 0). \qquad \textbf{(25)}$$

The stationary points have always existed, since $\beta_1 < 0$. A linearization in the vicinity of these points results in the expression:

$$\mathbf{D} = \begin{pmatrix} 0 & 1 \\ \pm\sqrt{-\beta_1} & \beta_2 \pm \sqrt{-\beta_1} \end{pmatrix}. \qquad \textbf{(26)}$$

From expression (26) follows that the stationary point $(+\sqrt{\beta_1}; 0)$ is stable, while the point $(-\sqrt{\beta_1}; 0)$ is the source at $\beta_2 > \sqrt{-\beta_1}$ or the sink at $\beta_2 < \sqrt{-\beta_1}$. Consequently, there is a Hopf bifurcation on the line $\beta_2 = \sqrt{-\beta_1}$, and a «saddle-knot» bifurcation is observed on the line $\beta_1 = 0, \beta_2 \neq 0.$ The Hopf bifurcation and the «saddle-knot» bifurcation are the only local bifurcations of the vector field in the plane that occur in typical uniparametric families.

To examine the stability of the Hopf bifurcation, we will make two variable substitutions in succession. The first substitution allows to bring the vector field to a standard shape. Let's suppose, that $\bar{q}_1 = q_1 + \sqrt{-\beta_1}$ and $\bar{q}_2 = q_2$. Then let's move on to the normal form of the vector field:

$$\begin{cases} \dfrac{d\bar{q}_1}{d\tau} = \bar{q}_2; \\ \dfrac{d\bar{q}_2}{d\tau} = -2\sqrt{-\beta_1}\bar{q}_1 + \bar{q}_1\bar{q}_2 + \bar{q}_1^2. \end{cases} \quad (27)$$

Now let's perform a linear transformation using the variables: $\bar{q}_1 = h_2$, $\bar{q}_2 = \sqrt{2\sqrt{-\beta_1}} \cdot h_1$. The matrix of this linear transformation consists of the real and imaginary parts of the eigenvectors corresponding to its eigenvalues $\lambda_{1,2} = \pm i\sqrt{2\sqrt{-\beta_1}}$. As a result, we obtain a system of differential equations, the linear part of which is written in the standard form:

$$\begin{cases} \dfrac{dh_1}{d\tau} = -\sqrt{2\sqrt{-\beta_1}} \cdot h_2 + h_1h_2 + \dfrac{1}{\sqrt{2\sqrt{-\beta_1}}}h_2^2; \\ \dfrac{dh_2}{d\tau} = \sqrt{2\sqrt{-\beta_1}} + h_1. \end{cases} \quad (28)$$

For the system (28), the first Liapunov value, that characterizes the stability of the limit cycle [27], is determined by the relation:

$$l_1 = \frac{1}{16\sqrt{-\beta_1}}. \quad (29)$$

Since $l_1 > 0$, it follows that the Hopf bifurcation is subcritical, and we have a family of unstable periodic orbits that surround the sink (steady focus) if the following relation takes place: $\beta_2 < \sqrt{-\beta_1}$, though these values differ little from each other.

Now let's check whether there is a global bifurcation of the separatrix loop type, for which the boundary cycle disappears, and the stable and unstable diversity of the saddle point «intersect». To examine such a bifurcation, we return to the system of equations (24) and apply scaling transformations: $q_1 = \varepsilon^2 g_1$. $q_2 = \varepsilon^2 g_2$. $\beta_1 = \varepsilon^4\theta_1$, $\beta_2 = \varepsilon^4\theta_2$, further on, we will also introduce a new time scale $\tau \to \varepsilon\tau$, where $\varepsilon \geq 0$. Then the system (24) takes the form:

$$\begin{cases} \dfrac{dg_1}{d\tau} = g_2; \\ \dfrac{dg_2}{d\tau} = \theta_1 + \varepsilon\theta_2 g_2 + \varepsilon g_1 g_2 + g_1^2. \end{cases} \quad (30)$$

Having analyzed the properties of the system (30) using the Melnikov function [21], we find the lines of global bifurcation in the plane (β_1; β_2). We obtain:

$$\beta_1 \approx -\frac{49}{25}\beta_2^2, \ \beta_2 \geq 0. \quad (31)$$

The true bifurcation line touches this semi-parabola at the point $\beta_1 = \beta_2 = 0$. It is also significant that the trace of the «saddle» magnitude is positive:

$$tr\mathbf{D} = \beta_2 + \sqrt{-\beta_1} \approx \frac{12}{5}\beta_2 > 0, \quad (32)$$

as result, the homoclinic orbit is the alpha-limit set for the nearest points.

Let's illustrate the behavior of the system when it deviates from the equilibrium position by conducting a numerical-analytical study. Let's consider the stability of the equilibrium position of the system (18), that corresponds to the point $z^* = v^* = L - k$. For this point, the system (18) takes the form:

$$\begin{cases} \dfrac{d\tilde{z}}{dt} = (2k - L)\tilde{z} - k\tilde{v} - \tilde{z}^2; \\ \dfrac{d\tilde{v}}{dt} = \omega\tilde{z} - \omega\tilde{v}. \end{cases} \quad (33)$$

The matrix of the linear part of the system of differential equations (33) has the following characteristic equation, that allows us to determine the eigenvalues of λ of this matrix:

$$\lambda^2 + (L + \omega - Lk)\lambda + \omega(L - k) = 0. \quad (34)$$

Given that L, k and ω are positive numbers, the condition for the stability of the equilibrium position is that the coefficients of quadratic equation (34) are positive. That's what we get:

$$\begin{cases} l + \omega - Lk > 0; \\ L - k > 0. \end{cases} \quad (35)$$

Assuming that $L > k > \omega$, we obtain $k < \dfrac{L + \omega}{2}$. Thus, we have defined the necessary constraint for the regulating parameter k.

Analysis of the properties of the quadratic equation (34) allows us to conclude about presence of a pair of complex-valued roots with a negative real part, indicating the presence of a stable focus near the equilibrium position under study.

As an illustration, some test calculations were carried out to simulate transitive processes when the system deviates from the state of equilibrium. Accordingly, the task was to select such values of the parameters of the system of differential equations that it would be possible to model the variety of transitive processes. With a sequential enumeration, it turned out that the most informative were the phase trajectories, obtained at the parameter values: $L = 1$, $k = \{0.4; 0.5; 0.6; 1.0\}$ and $\omega = \{0.25; 0,50\}$. Since it was necessary to determine precisely the partial solution of the system of the differential equations (33), for this purpose the following relations were considered as initial conditions: $\tilde{z}(0) = 0.2$, $\tilde{v}(0) = 0$. The results of the computations are presented in the form of graphs reflecting the cross-section of the phase trajectory of innovative diffusion in time by the planes $\tilde{z} = const$ and $\tilde{v} = const$ and at different values of the system parameters (*Fig. 2 – Fig. 5*).

As can be seen from the Fig. 2, at least two cycles take place, the amplitude of which gradually decreases until the system returns to a state of equilibrium. Let's check how the parameter ω, characterizing the inertia of the control system, affects this process (Fig. 3).

A comparison of the corresponding graphs in Fig. 2 and Fig. 3 shows that increasing the parameter ω leads to a faster transition of the system to a state of equilibrium. The amplitude of deviation from equilibrium increases significantly in the first half of the first cycle, and then rapid growth is replaced by the same rapid decrease, at this, the amplitude of fluctuations decreases faster than at ω = 0.25.

Further on, let's consider how the behavior of the system is affected by a change in the parameter *k*, that characterizes the pressure of the control influence on the diffusion of innovative processes. The comparison will be made for the case ω = 0.25, since at this value of the parameter ω the return of the process of diffusion of innovations to a steady state is characterized by quite distinct fluctuations. The Fig. 4 shows the cross-sections of the phase trajectory of the system at *L* = 1; *k* = 0.4; ω = 0.25. A comparison of the corresponding graphs in Fig. 2 and Fig. 4. shows that the period of fluctuations in the corresponding period of transition to equilibrium remains the same, but with a decrease of *k*, the amplitude of fluctuations at the first stage increases, and then rapidly decreases in terms of time.

At *k* > 0.5, it becomes impossible to return the system to a state of equilibrium. There comes a catastrophic breakdown of stability (Fig. 5). Furthermore, this breakdown occurs at the moment when, at lower values of the parameter *k* the system passes the lower point of the first cycle of fluctuations.

Similar results will be obtained for other combinations of parameters, provided that *k* > 0.5.

Thus, the analysis of the results of numerical experiments shows that for sets of parameters, when conditions

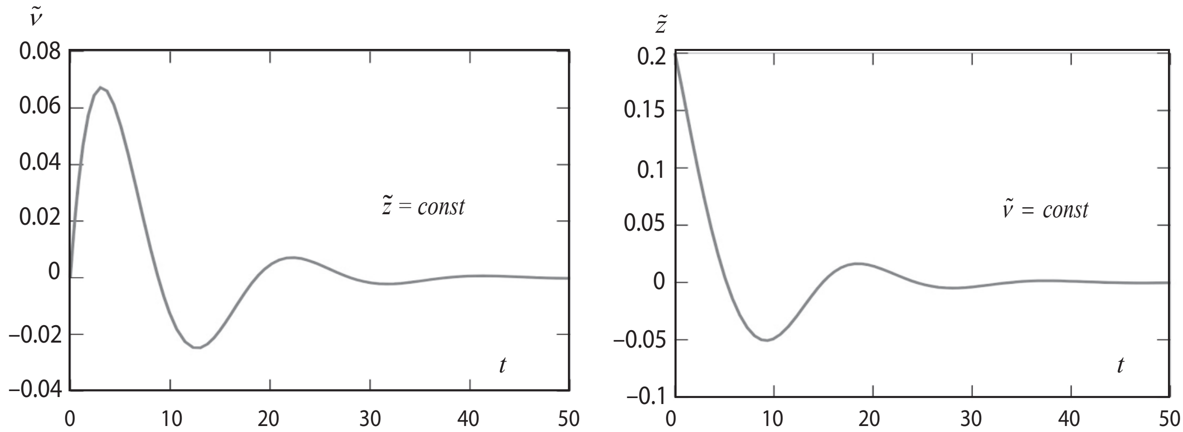

Fig. 2. The cross-section of the phase trajectory of the system development at the parameter values: L = 1; k = 0.5; ω = 0.25

Source: developed by the authors.

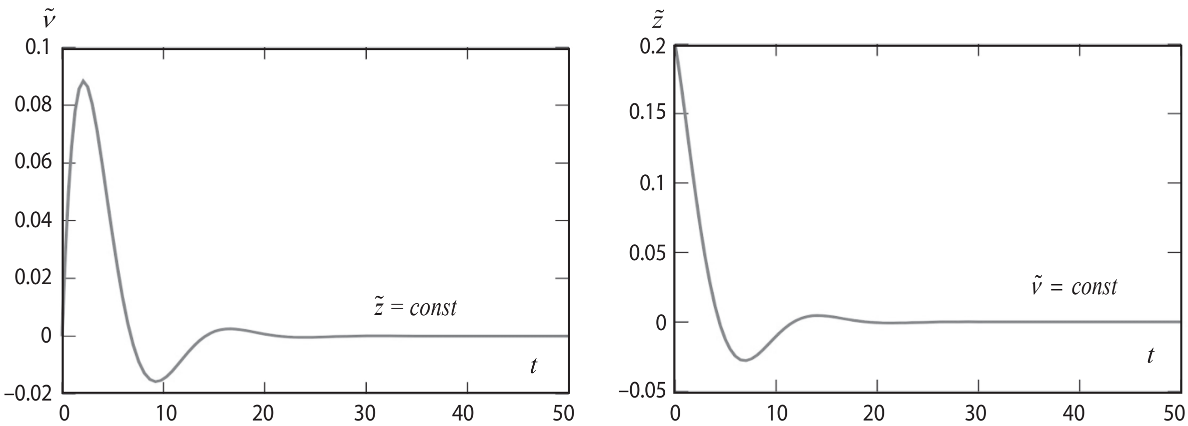

Fig. 3. The cross-section of the phase trajectory of the system development at the parameter values: L = 1; k = 0.5; ω = 0.5

Source: developed by the authors.

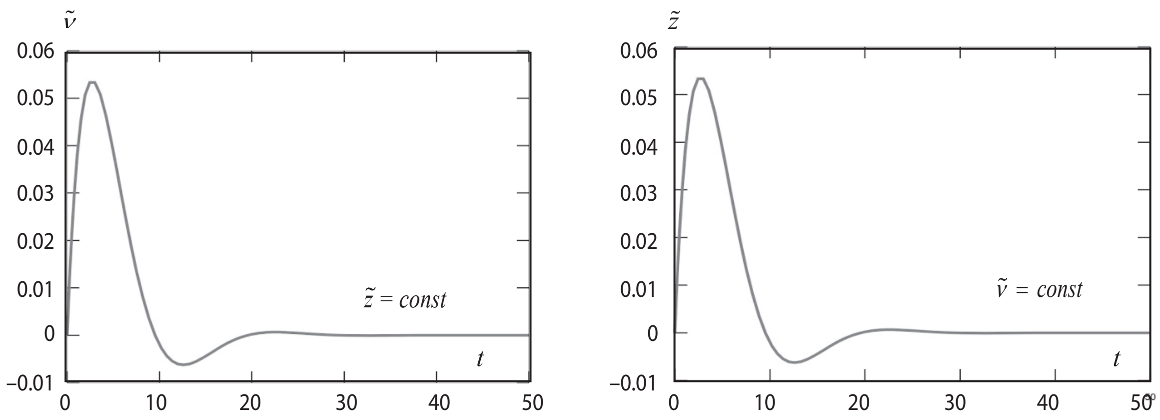

Fig. 4. The cross-section of the phase trajectory of the system development at the parameter values: L = 1; k = 0.4; ω = 0.25
Source: developed by the authors.

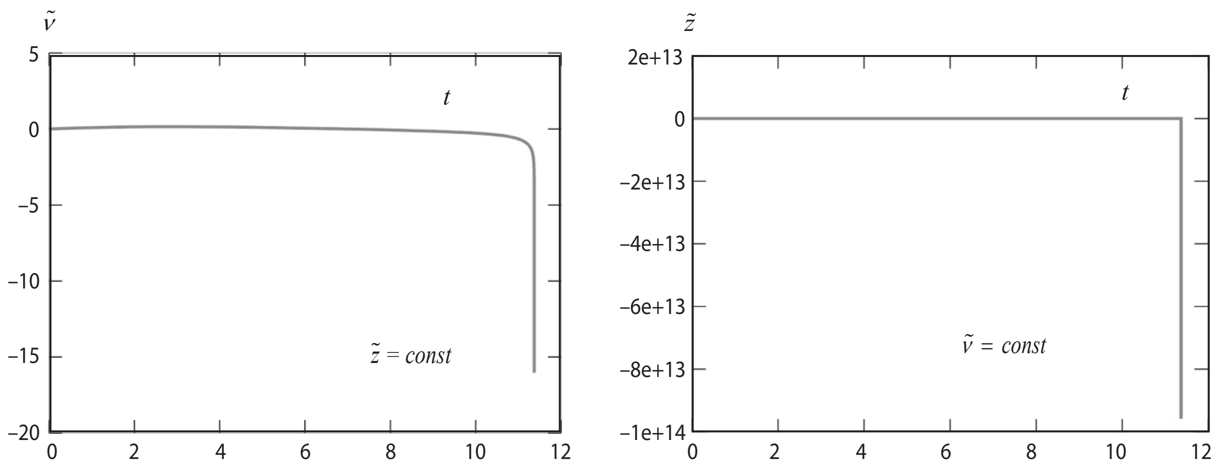

Fig. 5. The cross-section of the phase trajectory of the system development at the parameter values: L = 1; k = 0.6; ω = 0.25
Source: developed by the authors.

(35) and $0 < k < 0.5$ are met, the solution of the system of differential equations (33) with respect to the significant indicator, which characterizes the process of diffusion of innovations as a system with feedback, taking into account the overregulation for a finite number of time steps, acquires a constant value, that is, the system approaches the state of equilibrium. At $k > 0.5$, a return to a state of equilibrium becomes impossible. Thus, thanks to the computational experiment, the presence of the area of parameters of the control influence, which is aimed at ensuring a certain level of equilibrium of the dynamic process of evolution of an innovative product, is demonstrated.

CONCLUSIONS

The paper applies the method of nonlinear system dynamics to modeling the diffusion of innovations at the present stage of economic development, that allows to carry out a qualitative analysis (along trajectories in phase space) of the process of innovation diffusion under the conditions of control influence. Owing to the carried-out analysis, it can be concluded that the presence of nonlinearity leads to fundamental changes in the behavior of the system depending on the direction and intensity of this influence. As a result, the system can become structurally unstable, that leads to the appearance of undesirable bifurcations of various types, followed by a catastrophic loss of stability.

The influence of the control parameters on the nonlinear dynamic properties of the process of innovations diffusion as a complex ecosystem is analyzed. Particular attention was paid to the structural stability of the regulated innovation process, when both equilibrium positions are very close to each other in terms of parameter values. If the parameter k, that characterizes the feedback, is approximately equal to the equilibrium level L at $\mu_1 = 0$, then the two equilibrium positions «merge» into one and annihilate. Then a catastrophic loss of stability as the «fold-type» bifurcation is observed.

In the case when the parameter k is close in value to $0.5(L + \omega)$, an unstable limit cycle with a rigid self-fluctuation mode is born in the ecosystem of innovative development from a complex focus. The loss of stability in this case is irreversible (hysteresis) in nature.

The theoretical conclusions obtained in the study are confirmed through the use of simulation modeling. This mathematical instrumentarium can also be used to determine the behavior of real economic objects and systems, laying in the calculations the real values of the parameters that characterize this object, and the parameters of the control influence.

Since the described phenomena are associated with the abrupt volatile disturbances in equilibrium, they can lead to the collapse of the innovation market. This situation is especially dangerous when the regulation of the investment process is carried out at the State level. Therefore, in order to ensure a stable mode of functioning of the regulated innovation process, it is necessary to apply a system approach and determine the parameters of the system under which certain types of bifurcation can take place in the system.

CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interests in connection with the current research, including financial, personal, authorial, or any other that could affect the research and the results presented in this article. ■

BIBLIOGRAPHY

1. Olson D. L. (2003) Software Process Simulation, In: Encyclopedia of Information Systems. Ed.: Hossein Bidgoli. Elsevier, 2003. P. 143–153. DOI: https://doi.org/10.1016/B0-12-227240-4/00163-5
2. Barbrook-Johnson P., Penn A. S. System Dynamics. In: Systems Mapping. Palgrave Macmillan, Cham., 2022. P. 113–128. DOI: https://doi.org/10.1007/978-3-031-01919-7_8
3. Modelski G. What causes K-waves? *Technological Forecasting and Social Change*. 2001. Vol. 68. Iss. 1. P. 75–80. DOI: https://doi.org/10.1016/S0040-1625(00)00125-6
4. Slim A. Economic Cycles by Josef Schumpeter. In: A. Anquetil & T. Hoerber (eds). *Economic Theory and Globalization*. Palgrave Macmillan, 2019. P. 125–142. URL: https://hal.science/hal-03518472/document
5. Tyulin A. E., Chursin A. A., Ragulina J. V. et al. The development of Kondratieff's theory of long waves: the place of the AI economy humanization in the 'competencies-innovations-markets' model. *Humanities and Social Sciences Communications*. 2023. Vol. 10. Art. 54. DOI: https://doi.org/10.1057/s41599-022-01434-8
6. Moody B. J., Nogrady B. The Sixth Wave: How to Succeed in a Resource-Limited World. Random House, Sydney, 2010. 312 p.
7. Nair S., Paulose H. Emergence of green business models: The case of algae biofuel for aviation. *Energy Policy*. 2014. Vol. 65. P. 175–184. DOI: https://doi.org/10.1016/j.enpol.2013.10.034
8. MEX. Open Smart Manufacturing Ecosystem. URL: https://www.mexfinland.org/
9. Paasi J., Wiman H., Apilo T., Valkokari K. Modeling the dynamics of innovation ecosystems. *International Journal of Innovation Studies*. 2023. Vol. 7. Iss. 2. P. 142–158. DOI: https://doi.org/10.1016/j.ijis.2022.12.002
10. Valkokari K., Seppänen M., Mäntylä M., Jylhä-Ollila C. Orchestrating innovation ecosystems: a qualitative analysis of ecosystem positioning strategies. *Technology Innovation Management Review*. 2017. Vol. 7. Iss. 3. P. 12–24. DOI: https://doi.org/10.22215/timreview/1061
11. De Vasconcelos Gomes L. A., Facin A. L. F., Salerno M. S., Ikenami R. K. Unpacking the innovation ecosystem construct: evolution, gaps and trends *Technology Forecasting and Social Change*. 2018. Vol. 136. P. 30–48. DOI: https://doi.org/10.1016/j.techfore.2016.11.009
12. Phillips M. A., Ritala P. A complex adaptive systems agenda for ecosystem research methodology. *Technology Forecasting and Social Change*. 2019. Vol. 148. Art. 119739. DOI: https://doi.org/10.1016/j.techfore.2019.119739
13. Milling P. M., Maier F. H. System Dynamics Analysis of the Diffusion of Innovations. In: B. Dangerfield (ed.) *System Dynamics. Encyclopedia of Complexity and Systems Science Series.* Springer, New York, 2020. P. 459–489. DOI: https://doi.org/10.1007/978-1-4939-8790-0_124
14. Воронін А. В. Стійкість і біфуркації у моделях інвестиційних стратегій підприємства // Математичні методи і моделі в управлінні економічними процесами / за заг. ред. докт. екон. наук, проф. Л. М. Малярець. Харків : Вид. ХНЕУ ім. С. Кузнеця, 2016. С. 277–290.
15. Uriona M., Grobbelaar S. Innovation System Policy Analysis through System Dynamics Modelling: A Systematic Review. *Science and Public Policy*. 2019. Vol. 46. Iss. 1. P. 28–44. DOI: https://doi.org/10.1093/scipol/scy034
16. Smerichevskyi S., Mykhalchenko O., Poberezhna Z., Kryvovyazyuk I. Devising a systematic approach to the implementation of innovative technologies to provide the stability of transportation enterprises. *Eastern-European Journal of Enterprise Technologies*. 2023. Vol. 3. No. 13. P. 6–18. DOI:https://doi.org/10.15587/1729-4061.2023.279100
17. Xu X., Zou P. X. W. System dynamics analytical modeling approach for construction project management research: A critical review and future directions. *Frontiers Engineering Management*. 2021. Vol. 8. Iss. 1. P. 17–31 DOI: https://doi.org/10.1007/s42524-019-0091-7
18. Kagramanian A., Aulin D., Trubchaninova K. et al. Perspectives of multifunctional integrated suburban-urban rail transport development. *Scientific Journal of Silesian University of Technology. Series Transport*. 2023. Vol. 120. P. 105–115. DOI: https://doi.org/10.20858/sjsutst.2023.120.7
19. Логвінова М. О., Стець О. В. Економіко-математичне моделювання інноваційної діяльності підприємства. *Актуальні проблеми економіки та управління*. 2016. Вип. 10. URL: https://ela.kpi.ua/bitstream/123456789/22518/1/5_11_Logvinova.pdf
20. Zamlynskyi V. A., Stanislavyk O. V., Halytskyi O. M. et al. Conflict Dynamic Model of Innovative Development in the System of Ensuring the Competitiveness of an Enterprises. *International Journal of Scientific & Technology Research*. 2020. Vol. 9. Iss. 2. P. 5322–5325. URL: http://

lib.osau.edu.ua/jspui/bitstream/123456789/1998/1/Conflict-Dynamic-Model..._%281%29.pdf
21. Воронін А. В., Железнякова Е. Ю. Проблема стійкості керованого інноваційного процесу. *Вісник ХНУ імені В. Н. Каразіна. Серія «Міжнародні відносини. Економіка. Країнознавство. Туризм»*. 2020. Вип. 11. С. 46–53. DOI: https://doi.org/10.26565/2310-9513-2020-11-05
22. Schwab K. The Fourth Industrial Revolution. New York : Crown Publishing Group, 2017. 192 p.
23. Grybauskas A., Stefanini A., Ghobakhloo M. Social sustainability in the age of digitalization: A systematic literature Review on the social implications of industry 4.0. *Technology in Society*. 2022. Vol. 70. Art. 101997. DOI: https://doi.org/10.1016/j.techsoc.2022.101997
24. Pruyt E. Small System Dynamics Models for Big Issues: Triple Jump towards Real-World Complexity. Delft: TU Delft Library, 2013. 324 p.
25. Carrillo F., Verduzco F., Delgado J. Analysis of the Takens-Bogdanov bifurcation on M-Parameterized Vector Fields. *International Journal of Bifurcation and Chaos*. 2010. Vol. 20. No. 4. P. 995–1005. DOI: https://doi.org/10.1142/S0218127410026277
26. Qin B.-W., Chung K., Algaba A., Rodríguez-Luis A. J. High-Order Analysis of Global Bifurcations in a Codimension-Three Takens – Bogdanov Singularity in Reversible Systems. *International Journal of Bifurcation and Chaos*. 2020. Vol. 30. No. 01. Art. 2050017. DOI: https://doi.org/10.1142/S0218127420500170
27. Leonov G. A., Kuznetsova O. A. Lyapunov quantities and limit cycles of two-dimensional dynamical systems. *Analytical methods and symbolic computation. Regular and Chaotic Dynamics*. 2010. Vol. 15. P. 354–377. DOI: https://doi.org/10.1134/S1560354710020218

REFERENCES

Barbrook-Johnson, P., and Penn, A. S. "System Dynamics". In *Systems Mapping*, 113-128. Palgrave Macmillan, Cham., 2022. DOI: https://doi.org/10.1007/978-3-031-01919-7_8

Carrillo, F., Verduzco, F., and Delgado, J. "Analysis of the Takens-Bogdanov bifurcation on M-Parameterized Vector Fields". *International Journal of Bifurcation and Chaos*, vol. 20, no. 4 (2010): 995-1005. DOI: https://doi.org/10.1142/S0218127410026277

De Vasconcelos Gomes, L. A. et al. "Unpacking the innovation ecosystem construct: evolution, gaps and trends". *Technology Forecasting and Social Change*, vol. 136 (2018): 30-48. DOI: https://doi.org/10.1016/j.techfore.2016.11.009

Grybauskas, A., Stefanini, A., and Ghobakhloo, M. "Social sustainability in the age of digitalization: A systematic literature Review on the social implications of industry 4.0". *Technology in Society*, art. 101997, vol. 70 (2022). DOI: https://doi.org/10.1016/j.techsoc.2022.101997

Kagramanian, A. et al. "Perspectives of multifunctional integrated suburban-urban rail transport development". Scientific Journal of Silesian University of Technology. *Series Transport*, vol. 120 (2023): 105-115. DOI: https://doi.org/10.20858/sjsutst.2023.120.7

Leonov, G. A., and Kuznetsova, O. A. "Lyapunov quantities and limit cycles of two-dimensional dynamical systems. Analytical methods and symbolic computation". *Regular and Chaotic Dynamics*, vol. 15 (2010): 354-377. DOI: https://doi.org/10.1134/S1560354710020218

Lohvinova, M. O., and Ctets, O. V. "Ekonomiko-matematychne modeliuvannia innovatsiinoi diialnosti pidpryiemstva" [Economic and Mathematical Modeling of Enterprise Innovation]. *Aktualni problemy ekonomiky ta upravlinnia*, iss. 10 (2016). https://ela.kpi.ua/bitstream/123456789/22518/1/5_11_Logvinova.pdf

"MEX. Open Smart Manufacturing Ecosystem". https://www.mexfinland.org/

Milling, P. M., and Maier, F. H. "System Dynamics Analysis of the Diffusion of Innovations". In *Encyclopedia of Complexity and Systems Science Series*, 459-489. New York: Springer, 2020. DOI: https://doi.org/10.1007/978-1-4939-8790-0_124

Modelski, G. "What causes K-waves?" *Technological Forecasting and Social Change*, vol. 68, no. 1 (2001): 75-80. DOI: https://doi.org/10.1016/S0040-1625(00)00125-6

Moody, B. J., and Nogrady, B. *The Sixth Wave: How to Succeed in a Resource-Limited World*. Sydney: Random House, 2010.

Nair, S., and Paulose, H. "Emergence of green business models: The case of algae biofuel for aviation". *Energy Policy*, vol. 65 (2014): 175-184. DOI: https://doi.org/10.1016/j.enpol.2013.10.034

Olson, D. L. "Software Process Simulation". In *Encyclopedia of Information Systems*, 143-153. Elsevier, 2003. DOI: https://doi.org/10.1016/B0-12-227240-4/00163-5

Paasi, J. et al. "Modeling the dynamics of innovation ecosystems". *International Journal of Innovation Studies*, vol. 7, no. 2 (2023): 142-158. DOI: https://doi.org/10.1016/j.ijis.2022.12.002

Phillips, M. A., and Ritala, P. "A complex adaptive systems agenda for ecosystem research methodology". *Technology Forecasting and Social Change*, art. 119739, vol. 148 (2019). DOI: https://doi.org/10.1016/j.techfore.2019.119739

Pruyt, E. *Small System Dynamics Models for Big Issues: Triple Jump towards Real-World Complexity*. Delft: TU Delft Library, 2013.

Qin, B.-W. et al. "High-Order Analysis of Global Bifurcations in a Codimension-Three Takens – Bogdanov Singularity in Reversible Systems". *International Journal of Bifurcation and Chaos*, art. 2050017, vol. 30, no. 01 (2020). DOI: https://doi.org/10.1142/S0218127420500170

Schwab, K. *The Fourth Industrial Revolution*. New York: Crown Publishing Group, 2017.

Slim, A. "Economic Cycles by Josef Schumpeter". *Economic Theory and Globalization*, 125-142. Palgrave Macmillan, 2019. https://hal.science/hal-03518472/document

Smerichevskyi, S. et al. "Devising a systematic approach to the implementation of innovative technologies to provide the stability of transportation enterprises". *Eastern-European Journal of Enterprise Technologies*, vol. 3, no. 13 (2023): 6-18. DOI: https://doi.org/10.15587/1729-4061.2023.279100

Tyulin, A. E. et al. "The development of Kondratieff's theory of long waves: the place of the AI economy humanization in the 'competencies-innovations-markets' model". *Humanities and Social Sciences Communications*, art. 54, vol. 10 (2023). DOI: https://doi.org/10.1057/s41599-022-01434-8

Uriona, M., and Grobbelaar, S. "Innovation System Policy Analysis through System Dynamics Modelling: A Systematic Review". *Science and Public Policy*, vol. 46, no. 1 (2019): 28-44.
DOI: https://doi.org/10.1093/scipol/scy034

Valkokari, K. et al. "Orchestrating innovation ecosystems: a qualitative analysis of ecosystem positioning strategies". *Technology Innovation Management Review*, vol. 7, no. 3 (2017): 12-24.
DOI: https://doi.org/10.22215/timreview/1061

Voronin, A. V. "Stiikist i bifurkatsii u modeliakh investytsiinykh stratehii pidpryiemstva" [Stability and Bifurcations in Models of Enterprise Investment Strategies]. In *Matematychni metody i modeli v upravlinni ekonomichnymy protsesamy*, 277-290. Kharkiv: Vyd. KhNEU im. S. Kuznetsia, 2016.

Voronin, A. V., and Zhelezniakova, E. Yu. "Problema stiikosti kerovanoho innovatsiinoho protsesu" [The Problem of Sustainability of the Controlled Innovation Process]. *Visnyk KhNU imeni V. N. Karazina. Seriia «Mizhnarodni vidnosyny. Ekonomika. Krainoznavstvo. Turyzm»*, no. 11 (2020): 46-53.
DOI: https://doi.org/10.26565/2310-9513-2020-11-05

Xu, X., and Zou, P. X. W. "System dynamics analytical modeling approach for construction project management research: A critical review and future directions". *Frontiers Engineering Management*, vol. 8, no. 1 (2021): 17-31.
DOI: https://doi.org/10.1007/s42524-019-0091-7

Zamlynskyi, V. A. et al. "Conflict Dynamic Model of Innovative Development in the System of Ensuring the Competitiveness of an Enterprises". *International Journal of Scientific & Technology Research*, vol. 9, iss. 2 2020): 5322-5325. http://lib.osau.edu.ua/jspui/bitstream/123456789/1998/1/Conflict-Dynamic-Model..._%281%29.pdf

---

УДК 004.942:37(477)
JEL: H52; I22; I26; I29
DOI: https://doi.org/10.32983/2222-4459-2023-10-174-183

АНАЛІЗ ПОПИТУ НА ОСВІТНІ ПОСЛУГИ ЗВО УКРАЇНИ В УМОВАХ СУЧАСНИХ ВИКЛИКІВ

©2023 **КЛИМЕНКО Н. А., КОСТЕНКО І. С., БЄЛОУС А. О.**

УДК 004.942:37(477)
JEL: H52; I22; I26; I29

Клименко Н. А., Костенко І. С., Бєлоус А. О. Аналіз попиту на освітні послуги ЗВО України в умовах сучасних викликів

Мета статті полягає в дослідженні попиту на освітні послуги в Україні під впливом економічних, політичних і соціальних факторів, що діють у країні. Серед головних факторів, що впливають на попит освітніх послуг: пандемія COVID-19, повномасштабне вторгнення російської федерації на територію України та, як наслідок, – міграційні процеси, руйнування освітньої інфраструктури, зміна структури ринку праці, бюджетне обмеження, скорочення фінансування за рахунок домогосподарств тощо. Прогнозоване значення скорочення попиту на освітні послуги (кількість вступників) до 2025 р. на основі досліджених параметрів у середньому становить 10%. Проведено кореляційний та регресійний аналіз для дослідження попиту на освітні послуги закладів вищої освіти (ЗВО) залежно від основних демографічних, економічних і політико-соціальних показників. Згідно з аналізом кореляційної матриці факторами, що мають високий рівень тісноти взаємозв'язку та прямий вплив на кількість вступників до ЗВО, є кількість випускників шкіл, кількість населення віком 16–59 років та рівень зайнятості. Обернений вплив на кількість вступників мають такі фактори, як зниження витрат на освіту, пандемія COVID-19, окупація. У роботі розглянуто дослідження ефективності державного регулювання вступу на бюджет за окремими спеціальностями. Для цього було використано дані щодо результатів вступної кампанії 2023 р. з Єдиної державної електронної бази з питань освіти. Виявлено, що у 2023 р. найбільшим попитом користуються спеціальності, пов'язані із соціальним та філологічним напрямом (Психологія, Журналістика), а також ті, що мають усталене значення щодо престижу та працевлаштування (Стоматологія, Міжнародні відносини, спеціальності за IT-профілем тощо). Натомість найменший попит – у спеціальностей інженерного спрямування, де конкурс становить дві заяви на три бюджетні місця. У статті використано економетричні методи аналізу цифрової інформації, проведено аналіз моделі впливу між показниками прохідного балу та загальним конкурсом. Надано рекомендації щодо перегляду політики прийому та конкурсного відбору студентів за окремими спеціальностями, враховуючі існуючі усталені тенденції щодо попиту на інженерні спеціальності та з урахуванням фактора окупації території країни та, як наслідок, зміни структури виробництва та потреб на ринку праці.

Ключові слова: *ринок освітніх послуг, освітня послуга, вища освіта, попит, пропозиція, конкурс, прохідний (мінімальний) бал, економетричні моделі, коефіцієнт кореляції, коефіцієнт детермінації, похи-бка, війна, пандемія.*

Рис.: *6.* ***Табл.:*** *2.* ***Бібл.:*** *14.*

Клименко Наталія Анатоліївна *– кандидат економічних наук, доцент, доцент кафедри економічної кібернетики, Національний університет біоресурсів і природокористування України (вул. Героїв Оборони, 15, Київ, 03041, Україна)*
E-mail: *nklimenko@nubip.edu.ua*
ORCID: *https://orcid.org/0000-0003-0693-865X*
Researcher ID: *https://www.webofscience.com/wos/author/record/B-5849-2019*
Scopus Author ID: *https://www.scopus.com/authid/detail.uri?authorId=57210844921*

Костенко Інна Сергіївна *– доктор філософії, старший викладач кафедри економічної кібернетики, Національний університет біоресурсів і природокористування України (вул. Героїв Оборони, 15, Київ, 03041, Україна)*
E-mail: *kostenkois@nubip.edu.ua*
ORCID: *https://orcid.org/0000-0002-4987-3764*
Researcher ID: *https://www.webofscience.com/wos/author/record/B-7427-2019*
Scopus Author ID: *https://www.scopus.com/authid/detail.uri?authorId=58179184200*