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# A computer simulation of population reproduction rate on the basis of their mathematical models

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**Abstract.** The article deals with the adoption of computer modeling as one of the leading areas of introduction of modern information technology in the modernization of content, forms and methods of teaching. In order to implement interdisciplinary integrated learning, the possibilities of interdisciplinary integration of learning content have been identified, the practice of using software environments in the process of modeling biological problems based on mathematical models has been analyzed, the possibilities of implementing algorithms of mathematical models in computer modeling have been investigated. A set of research tasks in biology as a basis for the implementation of interdisciplinary integration: nature - mathematics - computer science has been introduced into the educational process. The mathematical models of Verhulst, Arim, Leslie and the exponential law of direct proportional dependence or proportional rate of reproduction depending on the number of individuals of a population were used to design computer models of reproduction of ecological processes. They were implemented using the computer mathematics system MathCad and using programming environments Python, C♯, C++. The expediency of the proposed method of interdisciplinary integration of learning content has been justified through a developmental and productive integrated approach, the use of certain collective forms of activity, the practical orientation of professional training disciplines to form algorithmic competence of students as a basis for professional competence in computer modeling of mathematical models of biological processes.

## 1. Introduction

### *1.1. Formulation of the problem*

Many talented young people who have a high level of knowledge in fundamental disciplines and successfully study computer technologies and software study in educational institutions of Ukraine. It is very important to single out such creative personalities in general, to consider their abilities, to help master creative thinking skills – to model and generate original ideas, to make informed decisions based on the use of mathematical methods in combination with modern information and communication technologies (ICT).

Today, education focuses on the widespread introduction of ICT and involves the modernization of content, forms and methods of teaching, there is already a steady trend to adopt computer modeling as one of the leading areas in research in various areas, including modeling of biological systems. "The logical basis for studying the phenomenon is the inference from general to partial. It allows the student in the process of developing a hypothesis and its solution to move from the already known general provisions of science and laws to the problem posed in the task" [1].

The term 'task' is defined as a set of actions designed to perform. In the scientific literature there is no unambiguous approach to the definition of 'research task', because the research task contains a problem that requires theoretical analysis, the use of one or more research methods with the help of which students can discover previously unknown knowledge [2].

The researched tasks have an integrative character which assumes besides knowledge of the field of modeling also use of the mathematical device, and it in turn, is the basis for computer modeling. Computer modeling in the context of our research is a way to solve problems. The tasks, in turn, precede computer simulation.

Designing tasks for computer modeling of biological processes based on their mathematical models requires an analysis of the development of opportunities for the use of ICT in modeling processes in various industries. The relevance of computer modeling is evidenced by numerous publications that are increasingly appearing in leading scientific and methodological publications in recent years.

Analysis of recent research and publications. General issues of computer modeling have been considered by such scientists as A. H. Balakireva [3], Yu. O. Zhuk [4], N. R. Balyk [5], S. O. Solovyov [6], I. O. Teplytskyi [7], etc. Modeling of pedagogical phenomena with the use of artificial intelligence is revealed in the works of B. B. Buyak [8], H. V. Tereshchuk, I. M. Tsidylo [9], etc.

A number of researchers have studied the peculiarities of application of computer simulation technologies. Santo Motta, Francesco Pappalardo – mathematical modeling of biological systems [10]. Zhiwei Ji et al. – mathematical and computational modeling in complex biological systems [11]. Hans Peter Fischer – mathematical modeling of complex biological systems [12]. David Gavaghan et al. – mathematical models in physiology [13]. Mark A. J. Chaplain – multiscale mathematical modelling in biology and medicine [14]. Peter Kohl et al. – computational modelling of biological systems: tools and visions [15]. Steven H. Wiley et al. – computational modeling of the EGF-receptor system: a paradigm for systems biology.

Integration is a general and multifaceted process of establishing links between information, knowledge, science, and ensuring their integrity and unified structure. One of the most important [16]. Vlyssides A., S. Mai and E. M. Barampouti – an integrated mathematical model for co-composting of agricultural solid wastes with industrial wastewater [17].

The use of the modeling method in the training of future specialists is presented in the works of S. V. Kozibroda [18], S. H. Lytvynova [2], Yu. O. Zhuk [19] and others.

In the monograph [6] the authors determine the conditions of professional training of future teachers of natural sciences and mathematics by means of computer modeling; a structural and functional model of training has been developed; socio-constructivist forms of organization, methods and tools for teaching computer modeling of future teachers of natural sciences and mathematics have been selected. "The main common feature of natural sciences, the foundations of which are laid in the content of education in natural sciences and mathematics, is the leading research method used in them – modeling, which in the learning process becomes a system-forming component of the content of education. Given that in computer science as a science and academic discipline, the method of modeling is also a leading method of research and teaching, in the process of teaching students of natural, physical, mathematical and computer science specialties of pedagogical universities it is necessary to master both computer modeling technology and teaching technology as research based on object-oriented approach to modeling and social-constructivist approach to learning".

New computer models unify ecological theory: computer simulations show that many ecological patterns can be explained by interactions among individual organisms [20].

The method of mathematical and, consequently, computer modeling is one of the forms of interdisciplinary activities that allows to integrate knowledge and activities from different fields of science, which greatly contributes to the development of research competence of students [21].

Mathematical and computer modeling contributes to the discovery, preservation and development of personal qualities of students. However, their use in the educational process will be effective only if a correct idea of the place and role of computer modeling in the educational process is formed [22, p. 9].

O. I. Teplytskyi expressed his opinion on the model of training future teachers of natural sciences and mathematics by means of computer modeling at the VI All-Ukrainian scientific-methodical seminar "Computer modeling in education". The future teacher must have the technology to design their own professional activities, be able to develop and apply innovative pedagogical technologies. In this regard, special attention in developing a model for training future teachers of natural sciences and mathematics was paid, on the one hand, to promising areas of development of educational systems (technological aspect), and on the other hand to the integration basics of teaching physics, mathematics, chemistry, biology, geography and computer science (fundamental aspect). Under this approach: 1) the subject of study becomes not just a student, but is formed and developed by a specialist, and the accumulated potential provides progressive self-development of professional competence in a modeled, simulated or real professional activity; 2) the student in the integrative course masters social-constructivist technologies of transformation of the content of training into ways of professional activity in fast-changing conditions [7].

Given the dynamic development of ICT, the diversity of methodological approaches, methods of using computer modeling systems to create projects for various research tasks and training of young people, such issues require additional research, refinements, approaches, models, developments, and new implementation methods.

The purpose of the article is to demonstrate the interdisciplinary integration of learning content through the theoretical substantiation of the technology of studying mathematical models of ecological systems using computer mathematics systems and programming languages.

## 2. Theoretical foundations of the study

To train specialists of a certain profile, it is advisable to use tools that develop skills and abilities, promote the development of design and research activities. Nowadays, the most promising method is STEM-education, because it is the integration of certain disciplines into a single system of education that has proved extremely effective. Built on interdisciplinary and applied approaches, STEM-education provides a mixed (interdisciplinary) educational environment in which students acquire theoretical knowledge and practical skills in the application of scientific methods of cognition. Today, the technology of integrated learning has become a leader in higher education institutions of Ukraine.

In the process of learning about the world, humanity widely uses a variety of models. Modeling is a universal method of scientific knowledge based on the construction, research and use of models of objects and phenomena. The most important type of modeling is mathematical models [23]. Along with the traditional areas of use of mathematics, new disciplines are increasingly involved in its scope of use.

Mathematical modeling involves the ability to program, actively use knowledge of natural sciences and their subsequent application in various fields of human activity to obtain new knowledge. The problem cannot be solved only by remembering the ready-made knowledge, it is necessary to think, look for connections and relationships, and select evidence [24]. Research tasks are not new, but the method of their consideration is still insufficiently studied, due to the high complexity of experiments, which are an integral part of the study [4].

Integration is a general and multifaceted process of establishing links between information, knowledge, science, and ensuring their integrity and unified structure. One of the most important aspects of integration in education, without a doubt, is the purposeful integration, synthesis of relevant educational components into an independent system of purpose, which aims to ensure the integrity of knowledge and skills of students.

The integration of educational components takes place in several areas and at different levels of higher education. In our study, we use internal disciplinary integration [25], which is carried out in the process of preparing a student of the first (bachelor's) level of higher education, involves a fragmentary process carried out at the level of each discipline and involves the search of interaction of different elements within the educational component and new approaches for the formation of students' ability to integrate computer modeling and mathematical models.

As we can see, the education of modern bachelors is component-centric, which is why the main focus here is on the internal integration of the content of educational material. The transition of education to a qualitatively new level is, in essence, a movement from intra-component to inter-component integration of learning content. This process is most clearly observed at the second (master's) level of higher education, namely in the process of writing a master's thesis using computer simulation.

## 3. Research methods and tools

The introduction of interdisciplinary integrated learning in the educational process allowed us to set the following tasks: 1) to trace the possibility of interdisciplinary integration of learning content; 2) to investigate the practice of using software environments in the process of modeling biological problems on the basis of mathematical models; 3) to investigate the integration of algorithms of mathematical models in the process of computer modeling.

The following theoretical and experimental research methods were used to solve the tasks: analysis of scientific, educational and methodological literature, search for modeling methods, analysis of applied mathematical packages and programming environments for the implementation of the created model; methods of mathematical modeling, time series analysis, regression analysis, methods of algorithmization and programming were used; analysis of the obtained results in accordance with the research problem, experiment (ascertaining, searching and forming) with the subsequent statistical processing of the results.

One of the conditions for the success of the introduction of integrated learning in the educational process is the use of information and communication technologies in the educational process, the teacher's knowledge of the functionality of modern digital technologies, and his/her practical skills to work with them [26].

When modeling environmental processes, programming languages (Python, C♯, C++) and ready-made software products (MathCad, MATLAB, Matematika, Microsoft Office software package, etc.) were used. Digital technologies can be used at all stages of preparation and execution of the modeling process. They do not replace the teacher, but only expand his/her capabilities.

One of the dangers of environmental modeling is the uncertainty of the models and the lack of supporting data. Only with the correct use of the model is it possible to study a wide range of uncertainties, indicating the limits of current knowledge and identifying critical information needed for management decisions. However, it is impractical to rely entirely on the conclusions of any model.

The integration processes proposed by us were carried out with the use of collaborative learning technology, namely, by involving the practice of interaction of participants in the educational process (students of bachelor's degree in chemical-biological, physical-mathematical and engineering-pedagogical faculties of Ternopil Volodymyr Hnatiuk National Pedagogical University), which allowed them to develop skills to work together in a small group and ensure quality educational outcomes [27].

The material for the study was a collection of red fistula, started by students of the Faculty of Chemistry and Biology during training in zoology in during 2017 and 2019. In total, students collected more than 1,000 specimens of the species. Partnership between undergraduates of the first year of study of chemical-biological, physical-mathematical and engineering-pedagogical faculties began in 2020 at the stage of processing the collected material.

## 4. The results of the study

The process of interdisciplinary integration of learning content was carried out by us by applying a number of mathematical models to the study of ecological systems using computer mathematics systems and programming environments, on the basis of which it was possible to implement specialized research.

Work began on modeling the dynamics of fluctuations in biomass and productivity of the population of grape snail (Helix pomatia), which has been consumed for centuries by residents of a number of European countries. Recently, intensive collection and procurement of mollusks for export abroad and for own use have begun in various regions of Western Ukraine. Uncontrolled collection of these animals can lead to the destruction of natural populations of Helix pomatia and, as a consequence, disruption of the cycle of substances in the ecosystems of the region. The task of studying the population growth dynamics was formed for students of two faculties who studied according to individual plans. Free schedule, consultations with teachers, and search on the Internet allowed them to successfully cope with this task.

The material was collected in the forests around the village of Velyki Chornokintsi, Chortkiv district, Ternopil region, during the spring-summer-autumn periods. Numerical modeling was carried out on the basis of two equations:

1) equation for calculating the population growth rate

$$V_n = rN - \frac{r}{k}N^2, r = \frac{\ln(N_2) - \ln(N_1)}{t_1 - t_2} \tag{1}$$

2) equation for calculating the maximum possible biomass

$$N(t) = N_0 e^{r(t-t_0)} \tag{2}$$

The predicted figures were obtained using the C♯ programming system. In order to verify the correctness of the solution to this problem using Microsoft Visual Studio C♯ 2010, a computer model was built in the Mathcad environment (figure 1).

The verification of the developed model was carried out according to the monitoring data of this population, which were obtained by students of the Faculty of Chemistry and Biology during the spring-summer-autumn training practices.

The analysis of the obtained results allowed us to draw conclusions about the adequacy of the selection of the mathematical functional by using which we obtained a solution. Both developed computer models obtained the same results [27].

The most available integrated characteristic of animal and plant populations is abundance, which is closely related to many other biota parameters. Therefore, traditionally in theoretical and practical ecology, the study of population dynamics is given paramount importance. However, many aspects of population estimation and analysis still remain controversial.

That is why under the condition of constant monitoring of the state of development and dynamics of changes and control over the rate of withdrawal of individuals from the population, as well as under the correct forecast, the population can exist indefinitely and maintain its productivity.

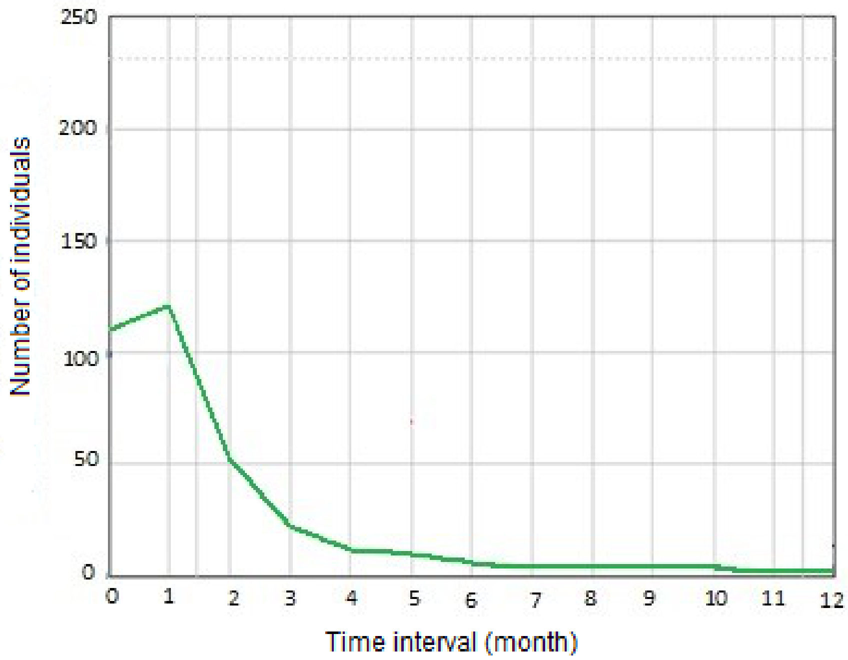


**Figure 1.** Model of population dynamics in a given area.

To date, there are many models for predicting time series: regression and auto-regressive models, neural network models, models of exponential smoothing, models based on Markov chains, classification models and others. Each of the existing models has advantages and disadvantages that can be significantly reduced by choosing the right field of application. It has been determined that the most promising direction of development of forecasting models in order to increase accuracy is the creation of combined and modified models.

Therefore, the next step was to use the ARIMA model [1] to predict the number of individual biological populations. Masters of physics-mathematics and chemistry-biology faculties were involved in the cooperation, who analyzed more than 40 models and created a modified autoregressive forecasting model, which has a higher efficiency of forecasting different time series compared to other models. A new method of forecasting was developed on the basis of the proposed model and software implementation of algorithms was performed; the efficiency of the offered forecasting model in solving the problem of forecasting of population time series has been estimated. The results of research in master's theses aroused great interest of specialists in this field.

The essence of building an Arim model for predicting population dynamics. Suppose there is a population in a certain environment. We will not impose restrictions on the area of location of individuals. Environmental monitoring has been conducted for a long time, as a result of which data on the number of specimens of the population in the specified time intervals have been collected. It is important that the recording of monitoring results was carried out with a given period, in our case – annually.

When constructing a graph based on the obtained data, you can see some explicit patterns (figure 2).

The time series has an obvious seasonality and an uncertain general trend to increase or decrease (figure 3).

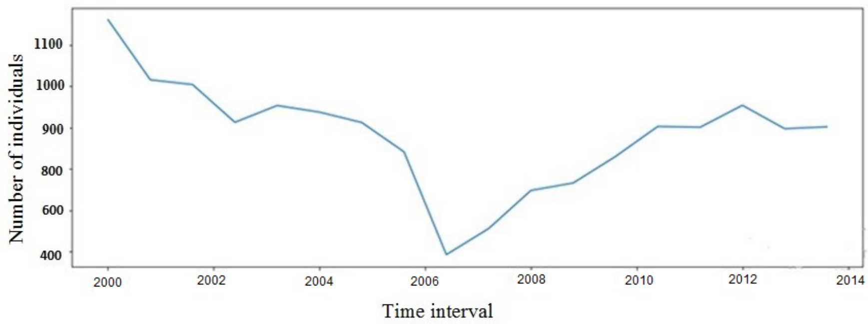


**Figure 2.** Annual readings of the number of individuals in the population.

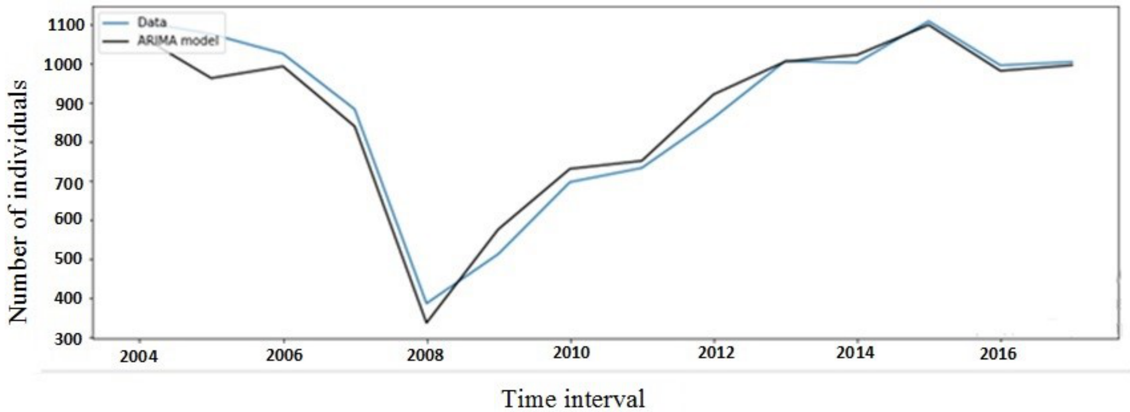


**Figure 3.** Checking the accuracy of the constructed model.

The construction of the model was based on the equation:

$$\triangle Dy_t = \sum_{i=1}^{n} \phi_i \triangle Dy_{t-i} + \sum_{j=1}^{q} \theta_j \epsilon_{t-j} + \epsilon_t, \epsilon_t \sim N(0, \sigma^2) \quad (3)$$

The resulting forecast can be seen in figure 4.

The implementation of the proposed forecasting model using the Python programming language showed high accuracy of time series forecasting, which allowed to build a forecast for 2018 - 2025 to determine the future values of the population. The developed forecasting method based on the ARIMA model is implemented in the form of a software application that performs population forecasting based on annual monitoring data [27].

Equally interesting was the study related to the forecast of individual population development in the framework of the Verhulst model. The model was built on the basis of the Verhulst equation using the knowledge of the ecology of the species. The forecast of population development for several years was calculated and the effect of population composition stabilization within this model was studied. The work was performed by a student of the Faculty of Engineering and Pedagogy in the framework of student research and submitted to the competition.

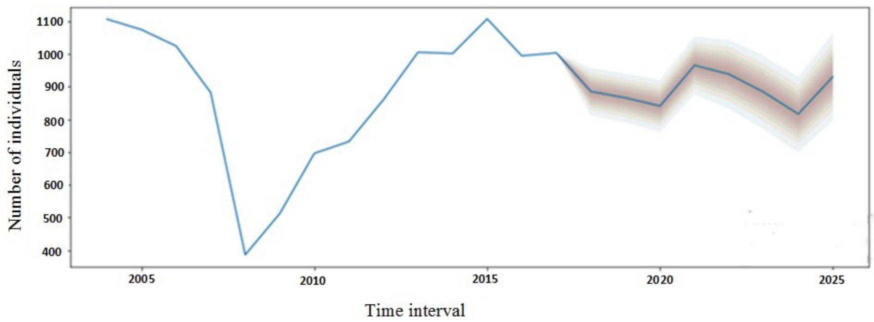


**Figure 4.** Forecast for 2018 - 2025.

Verhulst's idea [28] was to superimpose on exponential growth, expressed by the formula, some factor that characterizes the slowdown, increasing with population growth. The simplest possible assumption is that the degree of growth retardation for one individual is proportional to the size of the population, that is, the resulting growth rate is not $r$, but $r(1-\frac{N}{K})$, and determines the growth retardation. In this case, the logistic differential equation will take the following form

$$\frac{dN}{dt} = rN - \frac{rN^2}{K} = rN(1-\frac{N}{K}) \tag{4}$$

and its solution is expressed by the formula

$$N(t) = \frac{N_0 K e^n}{K - N_0 + N_0 e^n} = \frac{K}{1+(\frac{K}{N_0}-1)e^{-n}} \tag{5}$$

The distribution of the growth rate over the territory will be determined according to the formula

$$r(t)_i = \left[\left(\frac{Nf(t)_i}{N(t)_i} * 1,01\right) - D(t)_i\right] \tag{6}$$

where $Nf(t)_i$ is the birth rate distribution, $N(t)_i$ is the overall distribution, and $D(t)_i$ is the population mortality rate.

Estimation of the size of the selected population is presented in figure 5.

We were also extremely interested in research in the field of mathematical modeling done by Balakireva O. G., which were associated with the application of the Leslie's matrix model to ecological systems [3]. The problem was set in front of bachelor students studying computer modeling. The task was facilitated by the fact that the teachers presented an algorithm for solving this problem and theoretical development of the algorithm.

The study of population dynamics is associated with the construction of different population models, these models are often empirical and require additional justification or selection of unknown parameters. Mathematical models of the theory of population ecology can be divided into two groups: continuous and discrete. In continuous models, the number or population density of a population is considered to be a continuous function of time and spatial coordinates. Continuous models usually have the form of one or more differential equations. In reality, the population size is a discrete quantity that acquires certain values at fixed points in time. Discrete population values can be obtained from experimental data (laboratory or field) at discrete points in time. Meanwhile, the task of describing population dynamics leads to the analysis of a discrete system. Most discrete models of population dynamics describe only the change in the total population size (Malthus model, Verhulst model, Reeker model, etc.), without making

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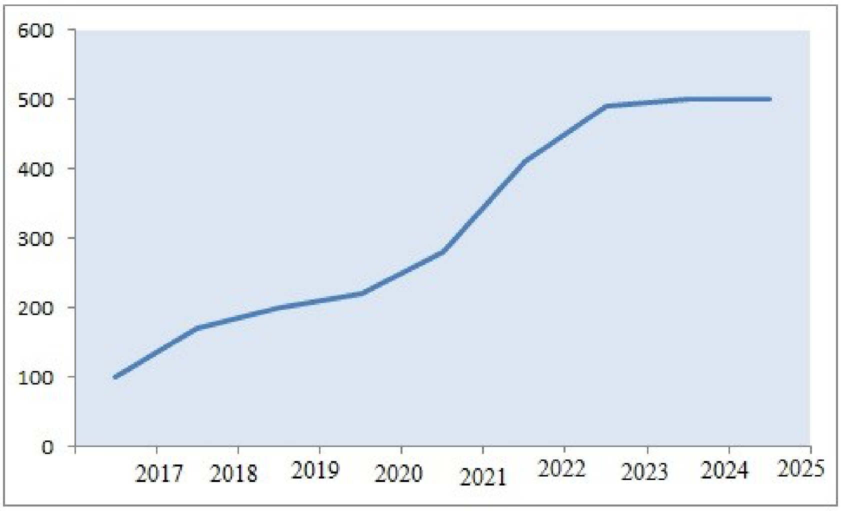


**Figure 5.** Estimation of the population of beetles from 2005 to 2021 according to accounting data and using the model.

any assumptions about the dependence of mortality and birth rate on the age of individuals. However, in many cases, taking into account the age structure of the population is of great importance.

Simple postulates about the relationship between the number of age groups lead to the socalled classical Leslie model, in which there is no change in the biological parameters of the population over time. But it is known that in practice these parameters change under the influence of climatic conditions, limited food resources and other environmental factors.

The essence of the model. Let the population contain n age groups. At each fixed point in time (for example, t0) the population can be characterized by a column vector

$$X(t_0) = [x_1(t_0), x_2(t_0), ..., x_n(t_0),]^T \tag{7}$$

where $x_i(t_j)$ is the number of individuals in the $i$-th age group. Survival and fertility rates change at each step.

Leslie's inhomogeneous model for predicting population development over time has the following form: $X(t_n) = L_{0,n}X(t_0), L_{0,n} = L_1 * L_2 * ... * L_n, n = 1, 2, ...$ where $L_i$ is the Leslie matrix in the i-th step

$$L = \begin{bmatrix} 0 & 0 & 0 & 0 & \alpha_k & \alpha_{k-1} & 0 & 0 \\ \beta_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \beta_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \beta_{n-1} & 0 \end{bmatrix} \tag{8}$$

In the first strip of this matrix there are birth rates, and the survival rates are under the diagonal.

The object of the study was the dynamics of the number of populations of red vole (Myodes glareolus Schreber, 1780; = Clethrionomys glareolus auct.). The study is based on experimental data obtained during 2017-2019. The software implementation of the computer model for predicting the number of population dynamics was carried out by us on the basis of the Leslie model [29].

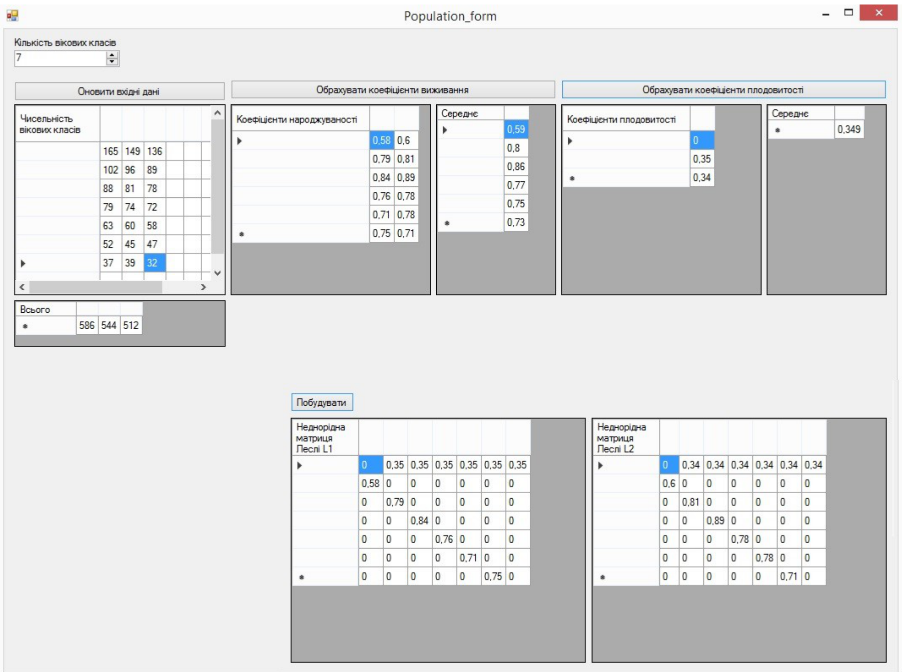


**Figure 6.** The form of the created application.

The graphical user interface (GUI) of the created application can be viewed in figure 6.

If all elements of the matrix are constants, then, depending on the eigenvalue $\lambda$, one of the three scenarios of population development is possible.

If $\lambda < 1$, then the population size decreases. If $\lambda = 1$, then the population size, starting from some point in time, will become constant; if $\lambda > 1$, then the population number will increase. We have $\lambda = 1.683$, so the population number increases (figure 7).

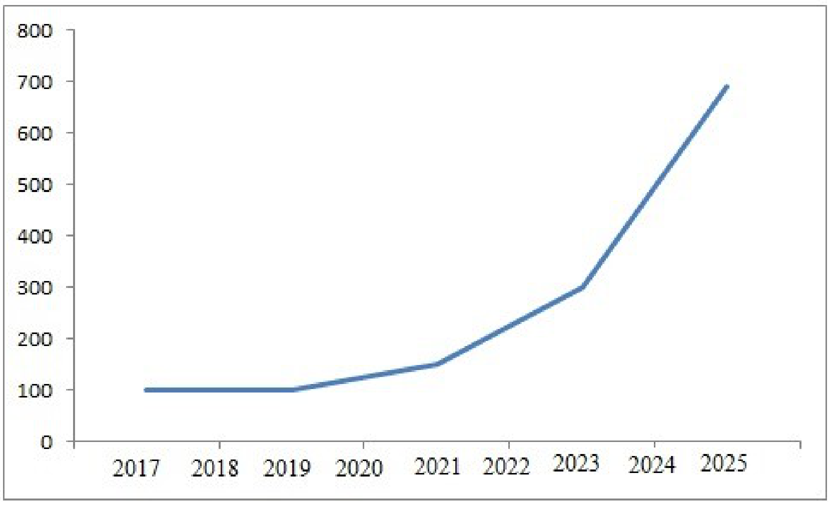


**Figure 7.** Graph of the growth of the population under study.

Any modeling process goes through several stages: observation of the object of modeling, accumulation of facts and phenomena, doing experiments; meaningful statement of the problem, schematization, formalization of facts, phenomena, certification, formulation of the technical task for model development; conceptual formulation of the modeling problem; mathematical formulation of the problem; checking the correctness of the model, consistency within the mathematical model, qualitative analysis of the model; selection and development of methods of solving, solution of the problem proper by analytical or numerical methods; checking the adequacy of the model to reality (model verification); practical use of the constructed model.

Mathematical modeling, in the case of a properly constructed model, helps to see what is difficult or impossible to verify in an experiment, allows you to reproduce such processes, the observation of which in nature would require a lot of effort and time. In mathematical models, you can 'consider' different options – to establish various connections, combine individual factors, simplify or complicate the structure of the system, change the sequence and strength of influence on it. All this makes it possible to better understand the mechanisms that operate in natural conditions.

The expediency of using the proposed method is justified by the following factors: students' comparative analysis of mathematical methods; making decisions on the feasibility and limitations of using a particular method; implementation of joint activities for modeling and development of software applications; mutual testing, debugging of created software products; analysis and results.

At realization of such technique collective forms of activity are used: pair work; group educational and cognitive activities; personal-role. Therefore, the following components of professional competence must be preformed in students: the ability to carry out information retrieval activities; skills of formalization and design of algorithms; proficiency in programming languages; skills of using digital technologies in solving practical problems; competency in mathematical apparatus and basic scientific concepts.

## 5. Conclusions and prospects for further research

Internal disciplinary integration can be implemented on the basis of the model nature mathematics computer science. The physical essence of this model of integration: natural processes are described in models by mathematical methods, followed by use in computer modeling.

The orientation of the educational process on the development-productive integrated approach has several positive aspects: the effectiveness of the formation of students' skills in modeling; the effectiveness of training in comparison with the subjects of professional orientation, which form the algorithmic competencies of students, through the possibility of intradisciplinary integration in the process of joint activities. Our research and our own experience suggest that the level of interest in performing such research among students is growing and contributes to the development of future professional competencies.

Intercomponent integration can take place between different disciplines of a certain cycle of both levels of higher education (for example, Zoology, Integrated Educational Practice Zoology, Phylogeny, Biogeography and Evolution of Life), and between disciplines of different cycles.

Verhulst's mathematical models were used to reproduce biological processes; Arima; Leslie and the exponential law of direct proportional dependence or proportional rate of reproduction on the number of individuals of a population. The implementation of the given mathematical models is possible using the programming environments Python, C♯, C++ and the mathematical package MathCad.

The application of interdisciplinary integration in teaching allowed to direct the content of training to get acquainted with the methods of modern systems research, to master the knowledge and skills of computer modeling for indepth study, quantitative and qualitative analysis of objects (phenomena, processes) in various fields.

At the present stage of integration in education it is necessary to restructure the activities of the teacher. Integration as a requirement to unite the components of learning objects into a single whole is a necessary didactic tool by which a holistic view of the object being studied is created, interdisciplinary competence is formed. With the help of multilateral relations, the foundation is laid for the formation of skills for a comprehensive vision of the problems of reality, diverse approaches to their solution.

Involvement of computer mathematics systems and the latest programming environments have contributed to the progress of the method of computer modeling of biological problems based on their mathematical models and popularization in everyday educational practice. The field of knowledge has been singled out, where basic research in mathematics and computer science is successfully combined with application in other sciences; mostly this process of creating a computer model is left behind. We see the prospect of further research in the study of the possibilities of software implementation of algorithms for describing the state of populations within a certain geographical area of Ukraine.

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