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MATHEMATICAL MODELS FOR DEVELOPING INTERACTIVE COMPONENTS OF DISTANCE EDUCATION SYSTEMS

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Abstract. A formalized mathematical model of a dynamic economic system with regulated parameters is presented, designed to study the mechanisms of economic equilibrium under the interaction of a producer, an aggregate consumer, and a price-regulating authority. The model also provides a methodological basis for creating an interactive computer simulator integrated into a distance learning system. It accounts for the closed nature of the economic environment, production constraints, consumer utility functions, and pricing dynamics. The behavior of the system under different supply and demand ratios is investigated, the causes of imbalances are identified, and the conditions for their elimination through price adjustments are determined. Special attention is paid to describing the transition of the system to an equilibrium state, the impact of unrealized stock and deferred demand, and the use of retail price coefficients as a stabilization tool. The dynamic mode of the model enables the analysis of system state changes across successive iterations, evaluating the effectiveness of pricing strategies and identifying critical operating regimes. The proposed approach ensures

flexible adjustment of demand and supply parameters, which increases the validity of economic process modeling in an educational environment. The implementation of the model as an interactive simulator promotes the development of analytical thinking, the formation of practical skills in economic modeling, and confirms the feasibility of using simulation modeling tools in the digitalization of education.

Keywords: economic system; production capabilities; utility function; simulation modeling; pricing; distance education.

Introduction. The active implementation of information technologies is one of the key trends in the development of modern education. Digitalization has significantly transformed the educational process, and one of its leading directions has been the widespread use of distance learning systems. Today, distance technologies are integrated into almost all levels of education, ensuring the continuity of the educational process and serving as an important tool for training specialists in various fields [1, 7].

Distance learning has acquired particular relevance under the conditions of full-scale war in Ukraine. Martial law, security threats, forced displacement of the population, and destruction of educational infrastructure have significantly limited the possibilities of traditional learning, making the distance format a necessary condition for preserving the accessibility of education and the continuity of the educational process [8, 9, 10, 11]. This necessitates the improvement of methodological and technological tools for e-learning and the development of new instruments for its support [9, 10, 11].

At the same time, distance learning has a number of limitations related to a decrease in the level of interaction between participants in the educational process and the insufficient interactivity of traditional online platforms [1, 3, 5, 6]. One of the promising ways to overcome them is the use of educational simulators, business games, and simulation modeling systems that reproduce real professional situations and contribute to the formation of practical competencies [12]. Their implementation is an important prerequisite for improving the quality of specialist training, primarily in the field of economics and management.

Purpose and Objectives of the Study. The purpose of the work is to develop a formalized mathematical model of an economic system with regulated parameters as a theoretical basis for creating computer simulators and trainers designed to study the mechanisms of achieving economic equilibrium and for use in distance learning systems.

The object of the study is the processes of modeling economic equilibrium, oriented towards further use in interactive simulation tools of distance learning.

The subject of the study is methods and tools for formalized modeling of economic equilibrium in dynamic economic systems, which provide a theoretical foundation for the development of interactive educational simulators.

To achieve this goal, it is necessary to solve the following main tasks:

– to develop a formalized mathematical model of an economic system taking into account the interaction of the producer, consumer, and price regulation authority,

suitable for the implementation of an interactive computer simulator in a distance learning system;

- to investigate the behavior of the model under various supply and demand ratios, determine the conditions for the emergence of economic imbalances, and justify compensation mechanisms to ensure the attainment of an economic equilibrium state;

- to analyze the mechanisms of the system's transition to an equilibrium state, evaluate the impact of unrealized stock and deferred demand on its dynamics, and form approaches to stabilizing the economic system under structural changes in supply and demand;

- to evaluate the effectiveness of using price regulation coefficients as a tool for stabilizing the economic system and increasing the accuracy of modeling its response to changes in price policy during the functioning of the educational simulator.

Analysis of Recent Research and Publications. The issues of digital transformation of education and the development of distance learning are actively investigated by both domestic and foreign scientists. A significant part of modern works is dedicated to improving e-learning technologies, their methodological support, and adapting the educational process to new social challenges.

In study [1], the features of continuous professional development of pedagogical workers under the conditions of society's digitalization and modernization of postgraduate education are considered. The author focuses on the psychological and pedagogical aspects of using distance technologies, analyzes the implementation of advanced training programs in distance and blended learning environments, and summarizes the experience of their practical application.

In work [2], modern educational technologies are investigated through the prism of a human-centered approach and the development of the information society. A generalized interpretation of educational technologies is proposed as a set of teaching methods, forms, and tools that combine information-communication and distance technologies for effective achievement of educational outcomes and professional development of learners.

The authors of work [3] analyzed modern theoretical approaches to distance learning and the specifics of their implementation in Ukraine. It is shown that domestic practice generally corresponds to European trends, and the development of digital technologies and changes in the information environment contribute to the spread of online education. Special attention is paid to the theories of autonomy, interaction, and industrialization of learning, as well as to the didactic principles that determine the specific nature of modern distance education.

In study [4], global trends in the development of digital universities and distance education as scalable platforms for providing educational services are considered. The authors emphasize that the concept of virtual universities, provided for by the Strategy for the Development of Higher Education in Ukraine for 2021–2031, is aimed at expanding access to education and implementing modern educational practices. At the same time, the rapid transition to distance learning revealed a number of organizational and material-technical problems.

In work [5], the specific aspects of using distance learning in military education under martial law conditions are investigated. The advantages of synchronous and asynchronous formats for organizing the educational process are analyzed, and the effectiveness of using BigBlueButton, Zoom, Microsoft Teams, Google Classroom, and Google Meet platforms to ensure continuity of learning is justified.

The authors of work [6] summarized the main challenges faced by the education system of Ukraine in 2022–2023. It was determined that the full-scale war accelerated the transition to distance learning, actualized the need to improve digital infrastructure, and fostered the search for new models of organizing the educational process oriented toward European standards.

In study [7, 8], the current state of e-education development, its advantages, and limitations are analyzed, and a comparative analysis of the implementation level of distance learning in different countries is performed. The authors investigated indicators of readiness for e-learning and noted that the COVID-19 pandemic became a powerful catalyst for the digitalization of education, stimulating the mass introduction of distance and blended forms of learning.

The conducted analysis of scientific works indicates that existing research is primarily focused on the methodological, organizational, and technological aspects of distance education. At the same time, insufficient attention is paid to the development of formalized mathematical models that can serve as a basis for creating interactive educational simulators and computer trainers. This confirms the relevance of research aimed at developing a mathematical apparatus for modeling economic equilibrium and its use in distance learning systems to increase their efficiency and adaptability to modern challenges.

Research Methods. This study employs methods of mathematical modeling of dynamic economic systems to formalize the interactions among a producer, the aggregate consumer, and a price-regulating authority within a closed economic environment. The model is based on the description of production capabilities, the consumer utility function, and pricing mechanisms, enabling the determination of optimal production and demand vectors for a given set of parameters. To analyze transient processes, an iterative approach is applied, involving the successive updating of price vectors, the evaluation of unsold inventories, deferred demand, and the redistribution of financial resources. This methodological framework makes it possible to investigate the conditions under which economic imbalances arise and are compensated, as well as to assess the impact of regulatory pricing coefficients on the attainment of the system's equilibrium state.

Research Results and Their Discussion. Let us consider the economic system as an interaction of three components: producers, consumers, and pricing authorities, whose operational algorithms form the model's trajectory [9-13, 14]. The producer's capabilities are described by the vector:

$$X = \{X_1, X_2, \dots, X_n\}, X \geq 0, X \in W, \quad (1)$$

where n is the product nomenclature; W is the set of production capabilities.

A price vector operates in the system, influencing the behavior of both producer and consumer. The producer's task is to determine production volumes according to the revenue maximization criterion [15]:

$$P \times X \rightarrow \max, X \geq 0, X \in W. \quad (2)$$

Solving (2) allows finding the optimal vector X^* , while the producer's revenue will be $C = P \times X^*$

We shall assume that the system is closed, meaning the sum C is transferred to the consumer. The latter forms the demand vector:

$$Y^* = \{Y_1^*, Y_2^*, \dots, Y_n^*\}, \text{ за умови } P \times Y \leq C. \quad (3)$$

When determining the demand Y^* from the aggregate consumer side, the task of utility maximization is solved, namely:

$$U(Y) \rightarrow \max, P \times Y \leq C, y \geq 0. \quad (4)$$

Then the equilibrium condition can be represented as $Y^* = X^*$, with the budget line $P \times X^* = C$. At the same time, the budget line B forms two sets W and S , namely:

$$S = \{X \mid U(X) \geq U(X^*)\}. \quad (5)$$

Let us define characteristic situations [16] for model (1)-(5):

– imbalance between supply and demand: $X^* \neq Y^*$;

the producer's optimal choice of nomenclature X^* is less valuable for the consumer: $U(X^*) < U(Y^*)$;

– the volume of nomenclature required by the consumer cannot be produced due to production constraints.

These states of the system indicate the occurrence of an economic imbalance caused by an ineffective price policy implemented at the stages of solving tasks (2) and (4).

Let us assume that the consumer does not know X^* , while their goal is to satisfy the demand Y^* . Then the actual production volume will be:

$$\tilde{X} = \min_{i \in n} \{X_i^*, Y_i^*\}, \quad (6)$$

the volume of unrealized stock will be $\Delta X = X^* - \tilde{X} \geq 0$, and the amount of deferred demand, respectively, $\Delta C = C - P \Delta X$. The model operates iteratively. At each iteration, the amount ΔC accumulates and forms a deferred demand fund. Let us consider the operation of the model over T iterations. At each iteration, a price vector $P(t)$ is formed, $t = 1, 2, \dots, T$. The initial values are $\Delta C(0) = 0, \Delta X(0) = 0$. At iteration t , the supply $\hat{X}(t)$ will be:

$$\hat{X}(t) = X^*(t) + \Delta X(t-1), \quad (7)$$

where $\Delta X(t-1)$ represents the stock from the previous stage, and $X^*(t)$ is the additional output volume.

The volume of demand at iteration t will be $Y^*(t)$, which is the result of solving (4) for prices $P(t)$:

$$C(t) = P(t) X^*(t) + \Delta C(t-1), \quad (8)$$

where $\Delta C(t-1)$ is the deferred demand at iteration $(t-1)$.

The state of the model at iteration t appears as:

– sales volume:

$$\tilde{X}(t) = \min\{\tilde{X}(t), Y^*(t)\}; \quad (9)$$

– unrealized stock:

$$\Delta X(t) = \hat{X}(t) - \tilde{X}(t); \quad (10)$$

– deferred demand:

$$\Delta C(t) = C(t) - P(t)\tilde{X}(t). \quad (11)$$

Let us consider the operation of the model for $n = 2$. According to the ratio of supply and demand, we have four situations:

1. $\Delta X_1 > 0, \Delta X_2 = 0$;
2. $\Delta X_1 = 0, \Delta X_2 > 0$;
3. $\Delta X_1 = \Delta X_2 = 0$;
4. $\Delta X_1 > 0, \Delta X_2 > 0$.

Let us consider the budget line $PX = q$ where q is the value of nomenclature X in prices P . We write the equilibrium condition $q = C$, taking into account that $q = p(X^* + \Delta X)$, $C = P \times X^* + \Delta C$, where ΔC is deferred demand:

$$\Delta C = P \times \Delta X. \quad (12)$$

If for current prices $P(t)$ we have a situation where $\Delta C \neq P \Delta X$, to achieve equilibrium, it is advisable to introduce a price adjustment coefficient η . Then the corresponding adjustment of the budget line position can be represented as: $\eta P \times X = C$. In the case of excessively large stock, it is necessary to choose $\eta > 1$. When the volume of supply exceeds demand, we choose $\eta < 1$. The exact value of η to achieve equilibrium can be found as:

$$\eta = \frac{P \times X^* + \Delta C}{P \times X^* + P \Delta X}. \quad (13)$$

Let us consider the operation with the coefficient η in situations 3 and 4. Situation 3. Demand is greater than supply, $\Delta C > 0$, product stock is zero, deferred demand is positive. We choose $\eta = 1 + (\Delta C / (P \times X^*)) > 1$, meaning we reduce deferred demand by increasing prices.

Situation 4. Supply significantly exceeds demand, $\Delta C = 0$. We choose $\eta < 1$, i.e., we initiate a «total clearance sale».

Analysis of the Two-Dimensional Case

In this case, two items of nomenclature are present in the system. We limit the description of production capabilities to the expression:

$$\frac{X_1^2}{a^2} + \frac{X_2^2}{b^2} = \mathbf{1}, \quad (14)$$

where a and b are the maximum possible production volumes of each type of product. The budget line tangent to the ellipse (14) at point (X_1^*, X_2^*) is written as:

$$\frac{X_1 X_1^*}{a^2} + \frac{X_2 X_2^*}{b^2} = \mathbf{1}, \quad (15)$$

then the price line $P \times X = d$ must satisfy the condition:

$$\frac{P_1 X_1}{d} + \frac{P_2 X_2}{d} = 1. \quad (16)$$

Based on (15) and (16), we obtain:

$$\frac{P_1}{d} = \frac{X_1^*}{a^2}, \frac{P_2}{d} = \frac{X_2^*}{b^2}, P_1 X_1^* + P_2 X_2^* = d, \quad (17)$$

and the solution to (17) can be represented as:

$$d = \sqrt{P_1^2 a^2 + P_2^2 b^2}, X_1^* = \frac{P_1 a^2}{d}, X_2^* = \frac{P_2 b^2}{d}. \quad (18)$$

The solution (18) allows finding the optimal output vector and revenue d . The modeling of consumer behavior is represented as:

$$\frac{(Y_1 - O)^2}{\alpha^2} - \frac{(Y_1 - O)^2}{(\alpha\beta)^2} = 1, \quad (19)$$

where β is the consumer preference coefficient, and the parameter O satisfies the requirement: $O > a, O > b$.

The consumer preference coefficient β allows modeling the relative utility of one product compared to another, namely: $\beta = 1$ – products are equal, $\beta > 1$ – demand for the first product is greater than for the second, $\beta < 1$ – demand for the second product exceeds demand for the first product.

The balancing condition can be defined as the intersection point of the line $P_1 X_1 + P_2 Y_2 = C$ with one of the ellipses (19), solving the system of equations:

$$Y_1^* = -\frac{P_1 C}{P_1^2 + P_2^2 \beta^2} + O, Y_2^* = -\frac{P_2 C \beta^2}{P_1^2 + P_2^2 \beta^2} + O. \quad (20)$$

Studies of the model indicate that achieving economic equilibrium in such a system is possible only if the mechanisms of demand, supply, and price regulation are coordinated. Due to the non-linear nature of the interaction between these components, even minor errors in price formation can significantly change the system's development trajectory and amplify its deviation from the equilibrium state. Situations where an imbalance already exists in the system, caused by deferred demand or excess supply, are particularly critical. In this case, any inaccuracies in price regulation acquire an accumulative effect and provoke further growth of structural distortions.

It has been established that under limited production resources and a significant initial deviation from equilibrium, the system is unable to return to a stable state on its own in the short term. Under such conditions, an important tool for stabilization is the use of retail price coefficients, which perform a compensatory function and allow adjusting the direction of the system's development.

In a state of economic equilibrium, a proportional change in the price level by itself does not lead to a disruption of the balance between supply and demand. However, in the presence of already formed disproportions — in particular, deferred demand or a shortage of certain goods — even minor errors in the mechanisms of price regulation can cause increased instability in the system. In such a situation, initial

deviations gradually accumulate and scale, which leads to an increase in the general economic imbalance and complicates the system's return to an equilibrium state.

Based on the developed model, an interactive computer trainer has been created that simulates the functioning of an economic system with regulated parameters. In the process of work, the user sets the initial conditions and pricing parameters, after which the model forms the behavior of the producer and consumer, taking into account production constraints, demand structure, and mechanisms of market interaction. The emergence of imbalances is displayed in the form of unrealized commodity stock or accumulated deferred demand.

The iterative nature of the trainer's operation allows analyzing the change of system states over time, evaluating the consequences of managerial decisions, and researching the effectiveness of various price regulation strategies. After completing the simulation, the system forms a sequence of actions and analytical results, which creates a basis for summarizing the obtained data and evaluating the effectiveness of the decisions made by the user.

Conclusions. The scientific novelty of the study lies in improving the approach to mathematical modeling of economic equilibrium by developing a dynamic model with regulated parameters that accounts for adaptive pricing mechanisms in a closed economic environment. Unlike existing models, the proposed approach is oriented not only towards researching the regularities of the economic system's functioning but also towards its use as a theoretical basis for creating interactive educational simulators and computer trainers in distance learning systems. This expands the possibilities for practical training of students by combining mathematical modeling with simulation learning technologies.

The practical value of the obtained results consists in the possibility of applying the developed model when creating interactive educational tools intended for researching the processes of formation and maintenance of economic equilibrium. The proposed approach ensures the modeling of interaction between the producer, the aggregate consumer, and price regulation mechanisms, allows analyzing the consequences of changes in supply and demand, evaluating the effectiveness of managerial decisions, and studying the behavior of the economic system in dynamics.

In the process of the study:

- a formalized mathematical model of a dynamic economic system with regulated parameters was developed, which reproduces the interaction of main market participants in a closed economic environment;

- the possibility of using the proposed model as a theoretical and methodical basis for creating interactive computer trainers in distance learning systems designed to study the processes of achieving economic equilibrium was justified;

- the regularities of the emergence of economic imbalances were investigated, the impact of unrealized stock and deferred demand on the dynamics of the system's functioning and the features of its transition to an equilibrium state were determined;

– the mechanisms of compensating for economic imbalances were analyzed and the effectiveness of using adaptive price regulation as a tool for stabilizing the economic system was evaluated;

– the prospects of implementing the developed model in the form of an interactive computer trainer were justified, the use of which in distance education systems will contribute to the development of analytical thinking and the formation of practical competencies of students.

The obtained results confirm the feasibility of using the proposed mathematical model as a base component of interactive educational systems oriented towards teaching economic and managerial disciplines, and also demonstrate the promise of applying simulation modeling to increase the effectiveness of distance learning.

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ІНТЕЛЕКТУАЛЬНИЙ ДОДАТОК ДЛЯ ОБРОБКИ ТА АНАЛІЗУ ДАНИХ СІЛЬСЬКОГОСПОДАРСЬКИХ ДРОНІВ

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Анотація. У межах дослідження було створено інтелектуальний вебзастосунок для аналізу даних дистанційного моніторингу сільськогосподарських угідь, який автоматизує перевірку приналежності зображень до поля, оцінювання частки рослинності, розрахунок індексу стану поля, аналіз параметрів NPK і рН, а також здійснює формування рекомендацій і накопичення результатів аналізу даних.

Ключові слова: бпла, точне землеробство, комп'ютерний зір, експертна система, вебзастосунок, аналіз ґрунту, підтримка прийняття рішень.