*Обґрунтовано необхідність використання нових форм організації виробництва та оцінки стійкості функціонування підприємств у динаміці. Запропоновано комплекс економіко-математичних моделей оцінки й аналізу стійкості функціонування підприємства в кризових умовах, що використовують логістичний підхід та апарат теорії автоматичного управління системами. Побудовано імітаційну модель оцінки стійкості функціонування підприємства*

*Ключові слова: стійкість функціонування, структурна модель, імітаційна модель, виробничо-збутова система, теорія автоматичного управління*

*Обоснована необходимость использования новых форм организации производства и оценки устойчивости функционирования предприятий в динамике. Предложен комплекс экономико-математических моделей оценки и анализа устойчивости функционирования предприятия в кризисных условиях, использующий логистический подход и аппарат теории автоматического управления системами. Построена имитационная модель оценки устойчивости функционирования предприятия*

*Ключевые слова: устойчивость функционирования, структурная модель, имитационная модель, производственно-сбытовая система, теория автоматического управления*

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# MODELLING OF THE ENTERPRISE FUNCTIONING STABILITY USING THE AUTOMATIC CONTROL THEORY APPARATUS

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## 1. Introduction

Modern Ukrainian society seeks to continually improve the level and conditions of life, which can only be achieved through economic growth of the country. In turn, economic growth can only be achieved through sustainable and stable development of enterprises – manufacturers of products that meet the growing needs of society. On the other hand, in any economic system, long-term economic growth and development cannot be monotonous being continually interrupted by periods of transition processes and permanent crises.

Crisis phenomena, instability and uncertainty in the economic environment are aggravated by unthoughtful long-term reforms, fierce competition and outdated technologies so characteristic for Ukraine. As a result, a large number of Ukrainian enterprises are characterized by non-fulfillment or failures in the implementation of plans, losses, loss of efficiency, i. e. instability. This leads to insolvency and bankruptcy of such enterprises, which further exacerbates the problems of the Ukrainian economy. Consequently, in today's economic conditions, the problem of the enterprise functioning stability and approaches to stability evaluation becomes particularly relevant.

The overcoming of the above-mentioned problems depends on the timely identification of the enterprise functioning stability threat, as well as the creation of mechanisms for effective management of its sustainable functioning. This becomes possible with the application of economic and mathematical modeling and logistic approach. The result of this approach application should be minimization of costs and increase of the enterprise efficiency.

Taking into account the above-mentioned, the actual task is the development, research and application of a complex of economic-mathematical models for assessment and analysis of the enterprise functioning stability. This complex will allow timely diagnosis of the enterprise instability and making effective management decisions.

## 2. Literature review and problem statement

In modern scientific publications, various approaches to modeling the stability of the enterprise functioning are considered. In the works [1, 2], the structure of the model basis of the crises early warning and prevention mechanism, aimed at ensuring the stable functioning and development of industrial-economic systems (IES) on different hierarchy levels is proposed. However, the issues related to the construction of the model complex were highlighted fragmentarily. In a number of sources, applied models of wind power plants stability assessment are considered, which allow forming a system of stability diagnostic indicators on the basis of signs complete and incomplete reduction methods [3, 4], carrying out classification of IES stability states on the basis of cluster analysis methods [3], DEA methods [5, 6], identifying the class of IES stability on the basis of classification trees [3], models of multiple choice [4], discriminant analysis [5]. It should be noted that along with the undoubted advantages, the above works do not adequately cover the issues of the comparative analysis of application effectiveness of various simulation methods. In addition, the terms of the model complex use in the IES operation are not fully considered.

The studies related to solving the task for constructing an integral indicator and predicting the level of the IES stability are sufficiently widely presented [7, 8]. Thus, the possibilities of using taxonomy methods [9, 10], Fourier analysis [9], fractal [11], bifurcation analysis [12] are explored. In the paper [13], the methods of crisis dynamics analysis and modeling are complemented by an approach based on the evaluation of the resonance interaction of cycle formation factors. The effectiveness of using the instrumental methods presented above in the comprehensive stability assessment, diagnostics of time series of integrated stability indicators, forecasting of crises is undoubted. However, it would be advisable to consider more fully the issues related to the implementation of a system approach in assessing the IES operation stability. In the works [14, 15], a set of models is proposed, which, based on the theories of fuzzy logic, neural networks, allows predicting the enterprise operation stability class. Possibilities for using neural network models to predict stability indicators are also considered in the papers [16, 17]. In the work [18], a multi-agent system with a bat-neural network is used for these purposes. To study the influence of factors in changing conditions, the authors of the work [19] suggest the use of a Bayesian network. The above methods have proven effective in investigating mass phenomena in credit scoring systems, bankruptcy monitoring, market value and investment management. However, the application of such an approach in the financial management system of enterprises with a flexible organizational structure is limited to the requirements for information provision.

Under conditions of crisis dynamics, the studies involving the use of a wide range of formalized and non-formalized methods for substantiating the choice of a strategy ensuring sustainable operation and development of enterprises were widely used. In the paper [20], a cognitive model of enterprise stability is proposed, which allows the formation of various scenarios for the development of a production system under various managerial influences and obstacles. In the works [21, 22], it is suggested to use simulation modeling based on the concept of system dynamics to justify the choice of a strategy that ensures the stable operation of the IES under conditions of the dominant threats. To substantiate the functional strategies of IES, in the works [23, 24], a multiagent approach is used that allows developing flexible models of system behavior taking into account the model agents individual behavior. Considering the undoubted prospects of the authors' research, it should be noted that in the above-mentioned works the issues of defining the parameters at which stable operation of separate subsystems of the IES as well as the IES in a whole are not sufficiently highlighted.

Summarizing the above analysis, it should be noted that, despite the effectiveness of the approaches proposed by the authors, the issues related to the enterprise functioning stability assessment in the dynamics and the effective management of this process remain insufficiently studied. Proposed in scientific publications [1–24] models, which are constructed for solving partial problems, solve specific scientific problems and are not aimed at complex solution. In addition, many methods and approaches for determining stability are too complicated, expensive and time-consuming, which is unjustified.

All this necessitates research on the development of economic and mathematical models of stability assessment based on the use of the classical apparatus of the automatic control theory (ACT) and logistic approach in economic systems [25]. This approach opens up the broad possibilities for a formal description of such complex systems as industrial enterprises and the application of well-known stability criteria to them.

## 3. The aim and objectives of the study

The conducted studies aimed to develop a complex of economic and mathematical models of enterprise operation stability assessment and analysis, using the logistic approach and the apparatus of the automatic control theory. Such models will allow timely diagnosis of the enterprise instability and making effective management decisions.

To achieve the aim, in the process of research the following tasks were solved:

– to develop a structural model and models of the enterprise functional subsystems dynamics;

– to construct a generalized transfer function of the enterprise and to determine the coefficients of the indicated function;

– to form a scenario model for assessing the enterprise operation stability and to build a simulation model for the scenario implementation.

## 4. Materials and methods of studying the enterprise functioning stability in crisis conditions

### 4. 1. Information base used in the study

Parametrization of the enterprise generalized transfer function and the scenario model formation were carried out using the economic indicators of two dairy complexes: State Enterprise "Experimental Farm "Kutuzivka" (Kharkiv region, Ukraine), Institute of Animal Husbandry of UAAS and LLC Agrofirm "Batkivshchyna" (Mykolaiv region, Ukraine). Among the indicators obtained from the financial reports of the complexes in 2016, those were selected that will be used to determine the parameters of the enterprise generalized transfer function coefficients (Table 1).

Table 1

Indicators of the enterprises in 2016

| No. b/o | Indicator | Unit | Indicator value | |
|---|---|---|---|---|
| | | | SE EF "Kutuzivka" | LLC Agrofirm "Batkivshchyna" |
| 1 | Average annual number of cows | heads | 975 | 600 |
| 2 | Gross milk yield | hundredweights | 54333 | 24030 |
| 3 | Amount of feed for cows | hw. of feed units | 66534 | 32740 |
| 4 | Salary | thousand UAH (thous. euros) | 288.2 (9.6) | 144.58 (4.8) |
| 5 | Petroleum, oil and lubricants (POL) | thousand UAH (thous. euros) | 74.7 (2.5) | 35.07 (1.2) |
| 6 | Amortization | thousand UAH (thous. euros) | 71.3 (2.4) | 31.9 (1.0) |
| 7 | Transportation service | thousand UAH (thous. euros) | 61.6 (2.0) | 20.6 (0.7) |
| 8 | Repairs | thousand UAH (thous. euros) | 112.7 (3.7) | 111.6 (3.7) |
| 9 | Low-value items (LVI) | thousand UAH (thous. euros) | 61.2 (2.0) | 8.1 (0.3) |
| 10 | Other costs | thousand UAH (thous. euros) | 0.3 (0.01) | 33.4 (1.1) |
| 11 | Overheads | thousand UAH (thous. euros) | 168.8 (5.6) | 45.9 (1.5) |

The determination of the demand level and market conditions was carried out on the basis of the dairy products sales prices and milk production volumes in all categories of farms in accordance with the Kharkiv and Mykolaiv regions in 2016, obtained from the State Statistics Service of Ukraine (Table 2) [26].

Table 2

The external environment of enterprises in 2016

| No. b/o | Indicator | Unit | Indicator value | |
|---|---|---|---|---|
| | | | Kharkiv region | Mykolaiv region |
| 1 | Prices of milk and dairy products at the beginning of the period | UAH/ton (euros/t) | 897.8 (29.8) | 1558.7 (51.7) |
| 2 | Prices of milk and dairy products at the end of the period | UAH/ton (euros/t) | 1099.3 (36.5) | 1694.0 (56.2) |
| 3 | The volume of milk supply on the market | thousand tons | 561.0 | 487.7 |
| 4 | The volume of milk demand in the market | thousand tons | 555.0 | 450.0 |
| 5 | Transportation time | days | 0.055 | 0.03 |
| 6 | Simulation period | days | 365 | 365 |

Thus, the information base for constructing the following set of models is the data of agribusiness enterprise financial reporting and the open statistical base of the State Statistics Service of Ukraine.

### 4. 2. A methodology for constructing a complex of models for estimating and analyzing the enterprise functioning stability

In the conditions of permanent crisis phenomena in the economy, the assessment of the enterprise functioning stability in the dynamics becomes especially important. To solve this problem and to recreate the system functioning algorithm in time, it will be effective to apply simulation modeling. The construction of the simulation model of the enterprise is proposed through a system of differential equations, which is one of the main tools for studying the stability in the classical apparatus of the ACT. This approach becomes possible due to the fact that the structure of the control scheme in systems of different nature (technical, biological, social, economic) is largely similar. Therefore, mathematical models can be used to describe the functioning of economic systems, which describe processes in technical systems.

It was proven that the most effective direction of the organization of enterprises involved in production and sales activities is the formation of a logistic production and sales system (PSS) [27]. The construction of such a system was carried out using a logistic approach and represents a solid organizational and economic structure consisting of the enterprise, suppliers of raw materials, components and products, consumers of finished products, and system of transport and warehouse facilities (Fig. 1, *a*).

The organizational and functional structure of the PSS is a complex cybernetic system with a plurality of material and information flows, managed by managers (block 1) with the help of feedback system. On these feedbacks, operative information arrives. In order to implement the principle of control by deviations, the system is closed with the help of the main feedback. This allows providing the system with the input signal proportional to the output value. Since this signal must act on the system in such a way that the deviation of the output value resulting from the perturbation is reduced, then the main feedback is negative. Along with the main feedback, to improve the accuracy of control in the system, local feedback that covers one or more links is also applied.

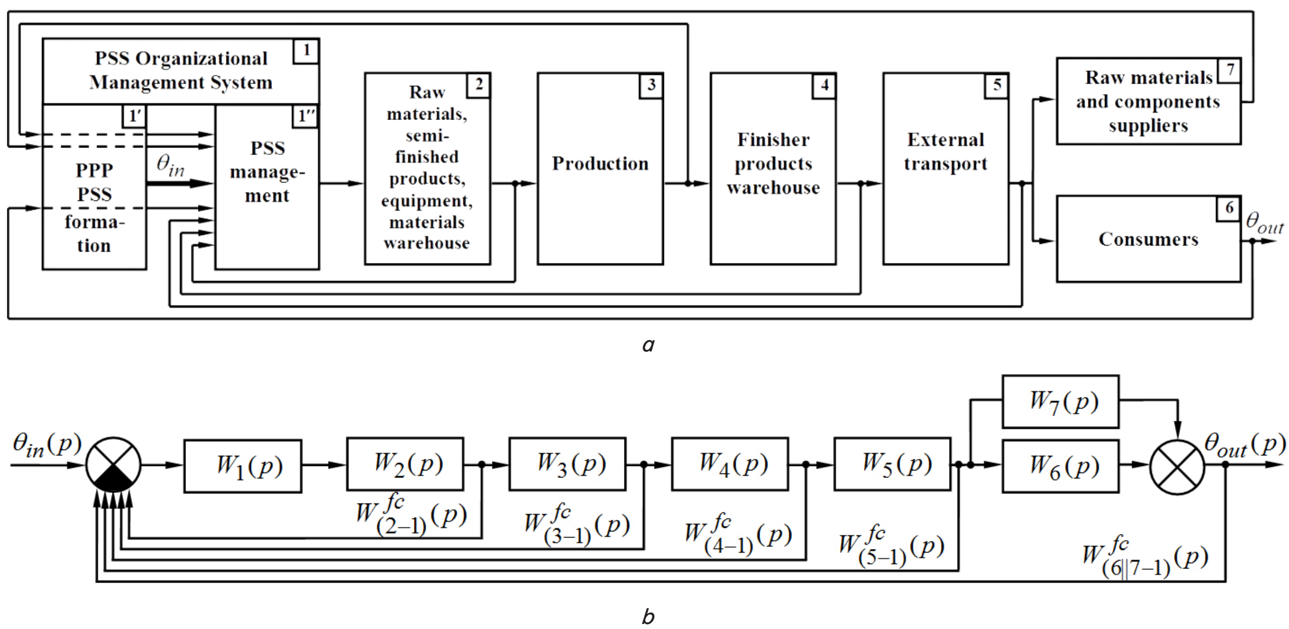



Fig. 1. Logistic production and sales system (PSS): *a* — scheme of organizational and functional structure; *b* — structural model; $\theta_{in}(p)$ — system input, prognostic production plan (PPP); $W_1(p)$, $W_2(p)$, ..., $W_7(p)$ — transfer functions of PSS blocks; $W^{fc}_{(2-1)}(p)$, $W^{fc}_{(3-1)}(p)$,..., $W^{fc}_{(6\|7-1)}(p)$ — transfer functions of feedback circuits; $\theta_{out}(p)$ — system output, implementation of the plan

The system consists of the complex itself (block 3), warehouses for raw materials, semifinished products, equipment, materials (block 2) and finished products (block 4), external transport (block 5), consumers (block 6), as well as suppliers of raw materials (block 7). With such a structure, the efficiency of the entire PSS is maximized.

System input $\theta_{in}$ (Fig. 1, *a*) is a prognostic production plan that is tracked and implemented by block 1. Output $\theta_{out}$ are finished products in the consumer field (block 6). The corresponding indicators of the prognostic production plan go to blocks 2–7, are compared with the possibilities of implementation and are taken into account in the process of PSS functioning.

A somewhat simplified management process of the PSS can be represented as systematic tracking of the system functioning in time by the block 1 when comparing outputs with the actual performance of the prognostic production plan. This comparison occurs for each local subsystem (blocks 2–7), and for the whole system.

In order to construct the simulation model of the enterprise, each block of the organizational-functional structure of the PSS is presented in the form of the corresponding interconnected dynamic links. As a result, we obtain the structural model of the enterprise in terms of the Laplace transformation (Fig. 1, *b*).

The determination of the types of dynamic links representing the functional blocks of the system on a structural scheme was carried out by compiling the dynamics equations of all the system elements. In drawing up these equations, the essence of economic phenomena occurring in one or another block was studied in detail, the methods of mathematical description of these phenomena were found, and the influence of all operating factors was taken into account. From the equations, it was possible to obtain the transfer and transition functions of the links, to determine transfer coefficients and time constants of the links, and therefore to establish the types of dynamic links (Table 3) [27].

Table 3

Transfer functions of the structural model parts taking into account the Laplace transformation, their coefficients and time constants

| No. b/o | The name of the structural model block and the type of the corresponding dynamic link | Transfer function $W_i(p)$ | Transfer coefficient $K_i$ | Time constant $T_i$ |
|---|---|---|---|---|
| 1 | Management of the production and sales system (aperiodic link) | $\frac{K_1}{T_1 p+1}$ | $\frac{Q_{su}}{Q_{dem}-\nu V_m}$ | $\frac{V_m}{Q_{dem}-\nu V_m}$ |
| 2 | Warehouse of raw materials, semi-finished products, equipment, materials (real-differentiating link) | $\frac{K_2 T_2 p}{T_2 p+1}$ | $\sqrt{\frac{2\cdot A\cdot S}{I}}$ | $\sqrt{\frac{2\cdot A}{I\cdot S}}$ |
| 3 | Production (aperiodic link) | $\frac{K_3}{T_3 p+1}$ | $\frac{Q_{rm}}{Q_{pp}-\nu V_{pp}}$ | $\frac{V_{pp}}{Q_{pp}-\nu V_{pp}}$ |
| 4 | Warehouse of finished products (real-differentiating link) | $\frac{K_4 T_4 p}{T_4 p+1}$ | $\sqrt{\frac{2\cdot A\cdot S}{I}}$ | $\sqrt{\frac{2\cdot A}{I\cdot S}}$ |
| 5 | External transport (delay link) | $e^{-p\tau}$ | – | – |
| 6 | Consumers (aperiodic link) | $\frac{K_6}{T_6 p+1}$ | $\frac{r}{s}$ | $\frac{1}{r}\cdot\ln\frac{K-P_0}{P_0}$ |
| 7 | Suppliers of raw materials and components (aperiodic link) | $\frac{K_7}{T_7 p+1}$ | $\frac{Q_{mp}}{Q_{ms}-\nu V_{ms}}$ | $\frac{V_{ms}}{Q_{ms}-\nu V_{ms}}$ |

The definition of the generalized transfer function of the enterprise was carried out taking into account the rules of the serial and parallel connection of the structural model links of the PSS, as well as the rules for finding the transfer function of the link covered by the feedback.

After collapse of the whole structural model of the enterprise (Fig. 1, *b*) in accordance with the given rules, collecting like terms and implementation of the substitution, the generalized transfer function of the PSS will be as follows [27]:

$$W_{1-7}(p)=\frac{\theta_{out}(p)}{\theta_{in}(p)}=$$

$$=\frac{Ap^3+Bp^2}{(a_6p^6+...+a_2p^2+a_1p+a_0)e^{p}+b_4p^4+b_3p^3+b_2p^2}, \quad (1)$$

where $W_{1\text{-}7}(p)$ – the generalized transfer function of the PSS; $\theta_{out}(p)$ – the output (finished products in the field of consumption); $\theta_{in}(p)$ – the input (prognostic production plan); $A$, $B$, $a_6$, $a_5$,..., $a_0$, $b_4$, $b_3$, $b_2$ – the coefficients of the generalized transfer function; $p$ – the complex Laplace operator; $e$ – the basis of the natural logarithm; $\tau$ – the time of cargo transportation.

The values of the generalized transfer function coefficients, representing the corresponding combinations of time constants $T_1$, $T_2$,..., $T_7$ and gain factors $K_1$, $K_2$,..., $K_7$ for links in the main circuit and feedback circuits $W^{fc}_{(2-1)}(p)$, $W^{fc}_{(3-1)}(p)$..., $W^{fc}_{(7-1)}(p)$ are presented in Table 4.

Table 4

The coefficients of the system generalized transfer function

| Coefficient | Formula for the coefficient calculation |
|---|---|
| $A$ | $K_1K_2K_3K_4T_2T_4(K_6T_7+K_7T_6)$ |
| B | $K_1K_2K_3K_4T_2T_4(K_6+K_7)$ |
| $a_6$ | $T_1T_2T_3T_4T_6T_7$ |
| $a_5$ | $T_4T_6T_7(T_1T_2+T_1T_3+T_2T_3+$ $+K_1K_2T_2T_3)+T_1T_2T_3(T_6T_7+T_4T_6+T_4T_7)$ |
| $a_4$ | $T_1T_4T_6T_7+T_2T_4T_6T_7+T_3T_4T_6T_7+K_1K_2T_2T_4T_6T_7+$ $+K_1K_2K_3T_2T_4T_6T_7+T_1T_2T_6T_7+T_1T_3T_6T_7+T_2T_3T_6T_7+$ $+K_1K_2T_2T_3T_6T_7+K_1K_2K_3K_4T_2T_4T_6T_7+T_1T_2T_4T_6+$ $+T_1T_3T_4T_6+T_2T_3T_4T_6+K_1K_2T_2T_3T_4T_6+$ $+T_1T_2T_3T_6+T_1T_2T_4T_7+T_1T_3T_4T_7+T_2T_3T_4T_7+$ $+K_1K_2T_2T_3T_4T_7+T_1T_2T_3T_7+T_1T_2T_3T_4$ |
| $a_3$ | $T_4T_6T_7+T_1T_6T_7+T_2T_6T_7+T_3T_6T_7+K_1K_2T_2T_6T_7+$ $+K_1K_2K_3T_2T_6T_7+T_1T_4T_6+T_2T_4T_6+T_3T_4T_6+$ $+K_1K_2T_2T_4T_6+K_1K_2K_3T_2T_4T_6+$ $+T_1T_2T_6+T_1T_3T_6+T_2T_3T_6+K_1K_2T_2T_3T_6+$ $+K_1K_2K_3K_4T_2T_4T_6+T_1T_4T_7+T_2T_4T_7+T_3T_4T_7+$ $+K_1K_2T_2T_4T_7+K_1K_2K_3T_2T_4T_7+$ $+T_1T_2T_7+T_1T_3T_7+T_2T_3T_7+K_1K_2T_2T_3T_7+$ $+K_1K_2K_3K_4T_2T_4T_7+T_1T_2T_4+T_1T_3T_4+T_2T_3T_4+$ $+K_1K_2T_2T_3T_4+T_1T_2T_3$ |
| $a_2$ | $T_6T_7+T_4T_6+T_1T_6+T_2T_6+T_3T_6+K_1K_2T_2T_6+$ $+K_1K_2K_3T_2T_6+T_4T_7+T_1T_7+T_2T_7+T_3T_7+K_1K_2T_2T_7+$ $+K_1K_2K_3T_2T_7+T_1T_4+T_2T_4+T_3T_4+K_1K_2T_2T_4+$ $+K_1K_2K_3T_2T_4+T_1T_2+T_1T_3+T_2T_3+K_1K_2T_2T_3+$ $+K_1K_2K_3K_4T_2T_4$ |
| $a_1$ | $T_1+T_2+T_3+T_4+T_6+T_7+K_1K_2T_2+K_1K_2K_3T_2$ |
| $a_0$ | 1 |
| $b_4$ | $K_1K_2K_3K_4T_2T_4T_6T_7$ |
| $b_3$ | $K_1K_2K_3K_4T_2T_4(T_6+T_7+K_6T_7+K_7T_6)$ |
| $b_2$ | $K_1K_2K_3K_4T_2T_4(1+K_6+K_7)$ |

The structural model of the PSS is converted into one equivalent block (Fig. 2) with a generalized transfer function (1), which is the basis of the simulation model of the enterprise. The input of such a block receives a prognostic production plan, and at the output, we receive finished products in the field of consumption.

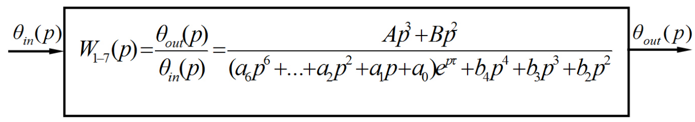



Fig. 2. Structural model of PSS in the form of an equivalent block

For the local criterion of optimality of the PSS functional subsystems in the management process, the minimization of the discrepancy can be accepted:

$$\Delta\theta=\theta^{pl}_{out}-\theta^{a}_{out}\rightarrow \min, \quad (2)$$

where $\Delta\theta$ – the value of discrepancy; $\theta^{pl}_{out}$ – the prognostic production plan, UAH; $\theta^{a}_{out}$ – the actual execution of the plan, UAH.

To determine the parameters of the enterprise structural model coefficients, the theoretical concepts of the modern economic theory and economic systems management organization were used, as well as the indicators presented in the information base of the research. The resulting parameters of the coefficients are shown in Table 5.

To investigate the enterprise functioning stability, the algebraic Hurwitz criterion and the graph-analytical criterion of Mikhailov were used. The choice of these methods is due to the fact that they are developed and successfully used in the ACT, allow investigating the stability in dynamics, and the process of determination of stability is well-algorithmized.

The algebraic Hurwitz criterion allows establishing if the system is stable or not fast, even without solving the characteristic equation. Thus, according to the Hurwitz criterion, the system (enterprise) will be stable, that is, the roots of the characteristic equation obtained from expression (1):

$$a_6p^6+a_5p^5+a_4p^4+a_3p^3+a_2p^2+a_1p+a_0=0, \quad (3)$$

will have negative valid parts if the determinant of Hurwitz and all its diagonal minors ($\Delta_i$) are positive.

Thus, the stability conditions have the form:

$$\Delta_6>0; \Delta_5>0; \Delta_4>0; \Delta_3>0; \Delta_2>0; \Delta_1>0. \quad (4)$$

The graph-analytic criterion of Mikhailov provides more information about the system behaviour. In it, the curve that describes the end of the vector obtained from the characteristic equation of the system (3) is used as a determinant, after the substitution $p=j\omega$, where $j=\sqrt{-1}$:

$$F(j\omega)=a_6(j\omega)^6+a_5(j\omega)^5+a_4(j\omega)^4+a_3(j\omega)^3+a_2(j\omega)^2+$$
$$+a_1j\omega+a_0, \quad (5)$$

when changing the frequency $\omega$ from $-\infty$ to $+\infty$. Since it is proven that the Mikhailov curve is formed as a vector hodograph and symmetric with respect to the abscissa axis, it is sufficient to change $\omega$ from 0 to $+\infty$.

Table 5

Parameters of the enterprise structural model coefficients for 2016

| The name of the parameter of the transfer function coefficients by the blocks of the PSS structural model | Parameter | Unit | Parameter value | |
|---|---|---|---|---|
| | | | SE EF "Kutuzivka" | LLC Agrofirm "Batkivshchyna" |
| 1. Management of PSS | | | | |
| Intensity of the product supply by the manufacturer | $Q_{su}$ | kg/day | 14886 | 14583 |
| Intensity of demand for goods among consumers | $Q_{dem}$ | kg/day | 14886 | 14583 |
| The volume of goods | $V_m$ | kg | 5433300 | 2683200 |
| 2. Warehouse of raw materials, semi-finished products, equipment, materials | | | | |
| Execution of one batch of orders (overhead) | $A$ | UAH (euros) | 2455.5 (81.46) | 2651.0 (88.0) |
| Intensity of demand (rate of inventory flow from the warehouse) | $S$ | kg/day | 18228.5 | 18681.5 |
| Storage costs per unit of raw material (specific costs) | $I$ | UAH/kg·day (euros/kg·day) | 0.0003 (0.00001) | 0.00037 (0.000012) |
| 3. Production | | | | |
| Intensity of raw materials purchase | $Q_{rm}$ | kg/day | 18228.5 | 18681.5 |
| Intensity of production | $Q_{pp}$ | kg/day | 14886 | 14583 |
| Storage volume of raw materials | $V_{pp}$ | kg | 546260 | 517398 |
| 4. Warehouse of finished products | | | | |
| Execution of one batch of orders (overhead) | A | UAH (euros) | – | – |
| Intensity of demand (rate of inventory flow from the warehouse) | $S$ | kg/day | – | – |
| Storage costs per unit (unit costs) | $I$ | UAH/kg·day (euros/kg·day) | – | – |
| 5. External transport | | | | |
| Volume of transported products | $V_t$ | kg | 14886 | 14583 |
| Product transportation time | $\tau$ | days | 0.055 | 0.04 |
| 6. Consumers | | | | |
| Price for goods in the market at the initial time | $P_0$ | UAH/kg (euros/kg) | 0.897 (0.03) | 0.680 (0.022) |
| The price growth rate | $r$ | UAH/day (euros/day) | 0.41 (0.014) | 2.01 (0.07) |
| The coefficient of self-limitation or intra-product competition | $s$ | – | 0.037 | 0.104 |
| 7. Suppliers of raw materials | | | | |
| Intensity of raw material production | $Q_{mp}$ | kg/day | 18228.5 | 18681.5 |
| Intensity of raw materials supply to consumers | $Q_{ms}$ | kg/day | 18228.5 | 18681.5 |
| Supply volumes of raw materials | $V_{ms}$ | kg | 546260 | 517398 |
| General options | | | | |
| Simulation period | $t$ | days | 365 | 365 |
| Coefficient of intensity | $v$ | 1/day | 0.0027 | 0.0027 |

The Mikhailov's hodograph is constructed on a complex plane in the coordinates $P(\omega)$, $Q(\omega)$, pre-splitting the expression $F(j\omega)$ into two parts – valid $P(\omega)$ and imaginary $Q(\omega)$. In order for a linear automatic control system having a characteristic equation of the $n$-th order was stable, it is necessary and sufficient to change $\omega$ from 0 to $\infty$ and the complete change of the vector argument $F(j\omega)$ was equal to $n\frac{\pi}{2}$, where $n$ – is the degree of the characteristic equation. In other words, the Mikhailov's curve must be placed in such a way as to cross over sequentially $n$ quadrants of the plane $P(\omega)-Q(\omega)$. Such a curve (stable system) is called correct.

The formulation of the criterion is retained when placing the roots on the imaginary axis. The presence of roots on the imaginary axis corresponds to the fact that the system is on the boundary of stability and the Mikhailov curve passes through the origin.

For the characteristic equation (5) when changing $\omega$ from 0 to $\infty$, the complete change of the vector argument $F(j\omega)$ will be equal to $3\pi$. That is, for the stable system the Mikhailov curve should be placed so that it would consistently cross six quadrants in the plane $P(\omega)-Q(\omega)$.

The problem with the coefficients of the characteristic equation, which tend to infinity, was solved by the method of finitization and reduction to the Cauchy task in the construction of the Mikhailov's hodograph.

Finitization is done by replacing the argument $\omega=t/(1-t)$, $t\in[0;1]$ in the characteristic equation (5). The resulting characteristic polynomial has the form:

$$R(t)=a_n(jt/(1-t))^n+$$
$$+a_{n-1}(jt/(1-t))^{n-1}+...+a_2(jt/(1-t))^2+a_1(jt/(1-t))+a_0. \quad (6)$$

Determination of the angle of the radius vector rotation around the origin of coordinates does not require knowledge of its modulus. Therefore, without losing information about the argument of a complex number, both parts of the equation can be multiplied by the real function $(1-t)^n$. These actions will change the modulus of the complex number, but will not change its argument. Finally, we have the expression:

$$R^*(t)=a_n(jt)^n+a_{n-1}(jt)^{n-1}(1-t)+...+a_2(jt)^2(1-t)^{n-2}+$$
$$+a_1(jt)(1-t)^{n-1}+a_0(1-t)^n, \quad (7)$$

where $R^*(t)$ – the finitized radius vector obtained from $F(j\omega)$.

As a result, for the stability analysis of an equation with constant coefficients, the determination of the radius vector rotation angle $R^*(t)$, $t\in[0;1]$ can be used instead of considering the vector rotation angle $F(j\omega)$, which modulus tends to infinity. The normalization of the vector was carried out by multiplying the real and imaginary parts of the equation by the fraction $(1+t)/R(t)$.

The curve, which describes the radius vector $R^*(t)$, is built on the integrated plane $P(t)$–$Q(t)$, pre-splitting the expression $R^*(t)$ into two parts – valid $P(t)$ and imaginary $Q(t)$.

## 5. Results of the enterprise functioning stability studies

The results of calculations of the generalized transfer function coefficients for enterprises, performed in the Mathcad package are given in Table 6.

For the enterprises under study, according to Table 6, the coefficients of the characteristic equation (3) were found and the Hurwitz determinant of the sixth order compiled according to this equation, as well as its five diagonal minors were calculated (Fig. 3).

As can be seen, in the first case, the determinant of Hurwitz and all of its five diagonal minors are positive (Fig. 3, *a*), that is, the conditions (4) are fulfilled. In the second case, the determinant of Hurwitz and three diagonal minors are negative (Fig. 3, *b*), therefore, the conditions (4) are not fulfilled. This means that, at the time of modeling, the functioning of the enterprise SE EF "Kutuzivka" is stable under this production plan, and the functioning of LLC Agrofirm "Batkivshchyna", on the contrary, is unstable.

However, as noted above, algebraic criteria allows making only qualitative judgments about the nature of processes, i.e. establishing if the process is stable or not. Concerning how fast the process is damped, the algebraic criterion of Hurwitz does not give an answer. It may turn out that the system is stable, but processes in the system are damped extremely slowly, and such a system turns out to be practically unsuitable.

The Mikhailov curve, constructed according to the data of the investigated enterprises for the characteristic equation (5) when changing ω from 0 to ∞ is shown in Fig. 4. In fact, it is the simulation model of the investigated enterprises built on the basis of generalized transfer functions.

As can be seen from Fig. 4, Mikhailov's hodograph cannot be obtained in the form of a spiral, and the angle of rotation of the radius vector can only be guessed. This is due to the fact that the coefficients of the characteristic equation (5) tend to infinity and have a large spread of values among themselves. As a result, with a fairly large ω, the Mikhailov curve also tends to infinity, and the graph does not display its initial areas.

Table 6

The values of the enterprise generalized transfer function coefficients

| No. b/o | Parameter | Transfer coefficient $K_i$ | Time constant $T_i$ |
|---|---|---|---|
| 1 | $Q_{su}$=14886 | $K_1 := \frac{Q_{su}}{Q_{dem} - \nu \cdot V_m}$ | $T_1 := \frac{V_m}{Q_{dem} - \nu \cdot V_m}$ |
| | $Q_{dem}$=14886 | | |
| | $V_m$=5433300 | $K_1$=68.888 | $T_1$=2.514×10$^4$ |
| 2 | $A$=2455.5 | $K_2 := \sqrt{\frac{2 \cdot A \cdot S}{I}}$ | $T_2 := \sqrt{\frac{2 \cdot A}{I \cdot S}}$ |
| | $S$=18228.5 | | |
| | $I$=0.0003 | $K_2$=5.463×10$^5$ | $T_2$=29.967 |
| 3 | $Q_{rm}$=18228.5 | $K_3 := \frac{Q_{rm}}{Q_{pp} - \nu \cdot V_{pp}}$ | $T_3 := \frac{V_{pp}}{Q_{pp} - \nu \cdot V_{pp}}$ |
| | $Q_{pp}$=14886 | | |
| | $V_{pp}$=546260.5 | $K_3$=1.359 | $T_3$=40.732 |
| 4 | – | $K_4$=14886 | $T_4$=1 |
| 5 | $\tau$=0.055 | – | |
| 6 | $P_0$=0.897 | $K_6 := \frac{r}{s}$ | $T_6 := \frac{1}{r} \cdot \ln\left(\frac{\frac{r}{s} - P_0}{P_0}\right)$ |
| | $r$=0.41 | | |
| | $s$=0.037 | $K_6$=11.081 | $T_6$=5.926 |
| 7 | $Q_{mp}$=18228.5 | $K_7 := \frac{Q_{mp}}{Q_{ms} - \nu \cdot V_{ms}}$ | $T_7 := \frac{V_{ms}}{Q_{ms} - \nu \cdot V_{ms}}$ |
| | $Q_{ms}$=18228.5 | | |
| | $V_{ms}$=546260.5 | K7=1.088 | T7=32.606 |
| 8 | ν=0.0027 | – | – |
| 9 | ω=0, 0.000001...0.00001 | $p(\omega)=i\times\omega,\ i=\sqrt{-1}$ | |
| 10 | $t$=0, 0.00001...1 | – | – |

$$a_6 = 5.93\times10^{9}\quad a_5 = 8.882\times10^{12}\quad a_4 = 4.42\times10^{15}\quad a_3 = 8.816\times10^{14}\quad a_2 = 2.297\times10^{13}\quad a_1 = 2.66\times10^{9}\quad a_0 = 1$$

$$\Delta6 := \begin{pmatrix} a_5 & a_3 & a_1 & 0 & 0 & 0 \\ a_6 & a_4 & a_2 & a_0 & 0 & 0 \\ 0 & a_5 & a_3 & a_1 & 0 & 0 \\ 0 & a_6 & a_4 & a_2 & a_0 & 0 \\ 0 & 0 & a_5 & a_3 & a_1 & 0 \\ 0 & 0 & a_6 & a_4 & a_2 & a_0 \end{pmatrix} \quad |\Delta6| = 2.113\times10^{66} \quad \Delta5 := \begin{pmatrix} a_5 & a_3 & a_1 & 0 & 0 \\ a_6 & a_4 & a_2 & a_0 & 0 \\ 0 & a_5 & a_3 & a_1 & 0 \\ 0 & a_6 & a_4 & a_2 & a_0 \\ 0 & 0 & a_5 & a_3 & a_1 \end{pmatrix} \quad |\Delta5| = 2.113\times10^{66}$$

$$\Delta4 := \begin{pmatrix} a_5 & a_3 & a_1 & 0 \\ a_6 & a_4 & a_2 & a_0 \\ 0 & a_5 & a_3 & a_1 \\ 0 & a_6 & a_4 & a_2 \end{pmatrix} \quad |\Delta4| = 0 \quad \Delta3 := \begin{pmatrix} a_5 & a_3 & a_1 \\ a_6 & a_4 & a_2 \\ 0 & a_5 & a_3 \end{pmatrix} \quad |\Delta3| = 3.46\times10^{43}$$

$$\Delta2 := \begin{pmatrix} a_5 & a_3 \\ a_6 & a_4 \end{pmatrix} \quad |\Delta2| = 0 \quad \Delta1 := a_5 \quad \Delta1 = 8.882\times10^{12}$$

*a*

$$a_6 = -2.547\times10^{7}\quad a_5 = -3.816\times10^{10}\quad a_4 = -1.9\times10^{13}\quad a_3 = -1.115\times10^{13}\quad a_2 = -3.26\times10^{11}\quad a_1 = -5.544\times10^{7}\quad a_0 = 1$$

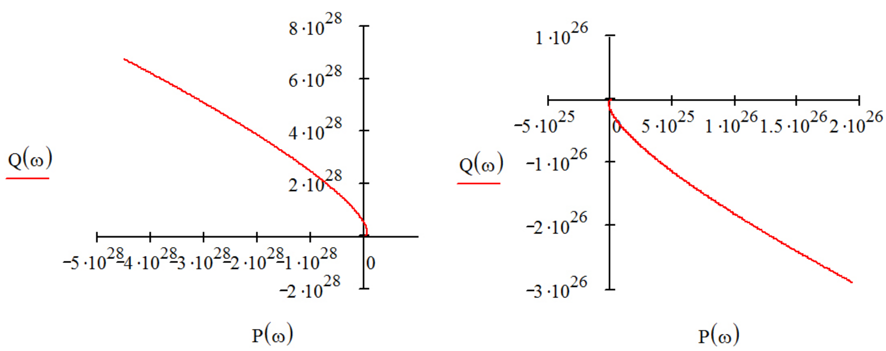
$$\Delta6 := \begin{pmatrix} a_5 & a_3 & a_1 & 0 & 0 & 0 \\ a_6 & a_4 & a_2 & a_0 & 0 & 0 \\ 0 & a_5 & a_3 & a_1 & 0 & 0 \\ 0 & a_6 & a_4 & a_2 & a_0 & 0 \\ 0 & 0 & a_5 & a_3 & a_1 & 0 \\ 0 & 0 & a_6 & a_4 & a_2 & a_0 \end{pmatrix} \quad |\Delta6| = -1.46\times10^{56} \quad \Delta5 := \begin{pmatrix} a_5 & a_3 & a_1 & 0 & 0 \\ a_6 & a_4 & a_2 & a_0 & 0 \\ 0 & a_5 & a_3 & a_1 & 0 \\ 0 & a_6 & a_4 & a_2 & a_0 \\ 0 & 0 & a_5 & a_3 & a_1 \end{pmatrix} \quad |\Delta5| = -1.46\times10^{56}$$

$$\Delta4 := \begin{pmatrix} a_5 & a_3 & a_1 & 0 \\ a_6 & a_4 & a_2 & a_0 \\ 0 & a_5 & a_3 & a_1 \\ 0 & a_6 & a_4 & a_2 \end{pmatrix} \quad |\Delta4| = 0 \quad \Delta3 := \begin{pmatrix} a_5 & a_3 & a_1 \\ a_6 & a_4 & a_2 \\ 0 & a_5 & a_3 \end{pmatrix} \quad |\Delta3| = -8.082\times10^{36}$$

$$\Delta2 := \begin{pmatrix} a_5 & a_3 \\ a_6 & a_4 \end{pmatrix} \quad |\Delta2| = 0 \quad \Delta1 := a_5 \quad \Delta1 = -3.816\times10^{10}$$

*b*

Fig. 3. The coefficients of the characteristic equation (3) and the Hurwitz determinant of the sixth order calculated for the enterprises: *a* — SE EF "Kutuzivka"; *b* — LLC Agrofirm "Batkivshchyna"



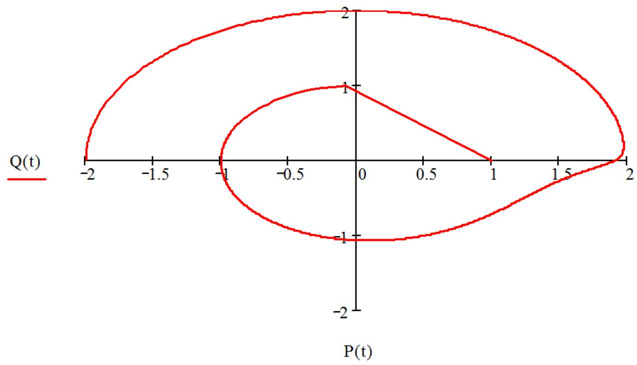

*a* *b*

Fig. 4. Mikhailov curve for the characteristic equation (5) when changing ω from 0 to ∞ built for the enterprises: *a* — SE EF "Kutuzivka"; *b* — LLC Agrofirm "Batkivshchyna"

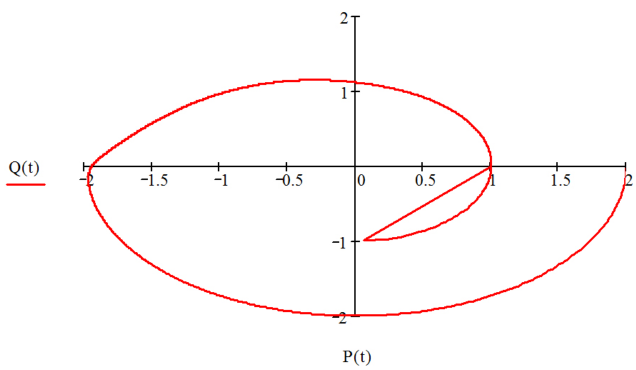
In this regard, it becomes unclear how the curve behaves: how many quadrants crosses and in what sequence. Consequently, it is impossible to make correct conclusions about stability in this case, and it is necessary to go to the adjustment of the simulation model.

The finitized Mikhailov hodograph for the investigated systems of the sixth order, constructed according to the data of the enterprises, is depicted in Fig. 5.

The finitized Mikhailov hodograph for the enterprise SE EF "Kutuzivka" is an integral spiral, which successively crosses six quadrants of the plane $P(t)-Q(t)$, that is, the curve is correct (Fig. 5, *a*). This means that, according to the Mikhailov's criterion, the functioning of the investigated enterprise is stable, and the adjustment of the simulation model can be considered complete.




*a*




*b*

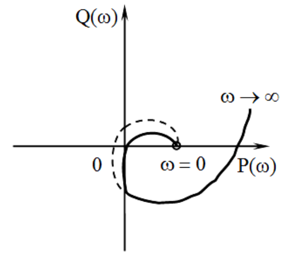
Fig. 5. Finitized Mikhailov's hodograph for the characteristic equation (7) when changing *t* from 0 to 1 built for the enterprises: *a* – SE EF "Kutuzivka"; *b* – LLC Agrofirm "Batkivshchyna"

For comparison, an appearance of a formalized Mikhailov hodograph built for the enterprise LLC Agrofirm "Batkivshchyna" is shown alongside (Fig. 5, *b*). As we see, the curve does not intersect six quadrants consistently, but makes a "loop", so it is wrong. This means that the operation of the mentioned enterprise was unsustainable.

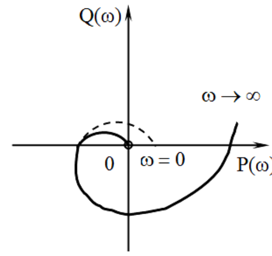
## 6. Discussion of the enterprise functioning stability results study and the determination of the stability margin

The analysis of the functioning stability of two enterprises by the algebraic Hurwitz criterion and the graph-analytic Mikhailov criterion was carried out. The first is actually a mathematical model for assessing the system's functioning stability, and the second one is a simulation model. Since simulation results coincide in both cases, we can assume that the simulation model constructed is adequate.

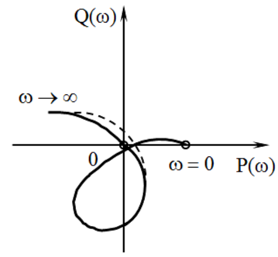
It should be noted that in addition to the above cases of stable and unstable systems, it may turn out that the system is on the verge of stability. In this case, there are two possible options of placement of the Mikhailov curve. One corresponds to the presence of imaginary roots (Fig. 6, *a*), and the other – to the presence of a real zero root (Fig. 6, *b*).




*a*




*b*




*c*

Fig. 6. Placement of Mikhailov's hodographs for a system that is on the verge of stability in the presence of: *a* – complex root; *b* – zero root; *c* – hodograph of an unstable system

A characteristic feature of the curve placement is that with an infinitely small deformation (shown by strokes in Fig. 6), the correct Mikhailov curve can be obtained. So, if the curve $F(j\omega)$ passes near the origin of coordinates, we can say that the system is near the limit of stability, that is, we can determine the degree of stability.

For an unstable system, it is also possible that the curve $F(j\omega)$ will pass through zero, but in this case, an infinitely small deformation does not significantly change the placement of the curve (Fig. 6, *c*).

The determination of the stability domain by the equations of the first approximation does not give full confidence that the enterprise functioning will be stable at all values of the parameters belonging to the selected area. The calculation of the areas of stability, taking into account the exact equations, is either impossible or loses its practical value as a result of bulkiness. Therefore, it is necessary to perform calculations on the approximate equations, and then introduce the correction coefficients (stability margin).

The need to determine the stability margin is due to the following circumstances:

– when compiling the original equations, only the basic laws of economic theory were taken into account and the secondary factors were rejected;

– the initial equation is linearized;

– economic indicators, which express the time constants and the gain factors of the units, are usually determined with the error;

– the calculation is conducted for typical conditions and the structural model of the PSS.

In reality, it is necessary to take into account the statistical nature of the external factors change and the distribution of parameters in different types of systems. Therefore, the application of such a quantitative characteristic as stability margin in the calculations is a kind of guarantee of stability in real conditions. Consequently, in case of negative factors influence, the system will remain stable for a certain time or will be on the verge of stability. How long the system will remain stable depends on the magnitude and duration of these factors.

The stability margin can be expressed in different ways, depending on the criterion, accepted as the basis of the calculation. Let us consider the order of the stability margin using the Mikhailov's criterion. If the system location at the stability limits is indicated by the fact that the curve passes through the origin, then the stability margin is given as the radius of the circle *r* with a center at the coordinates origin. Moreover, this circle should not cross the Mikhailov curve.

After analyzing the finitized Mikhailov hodograph for the investigated system of the sixth order depicted in Fig. 5, *a*, it can be revealed that the radius of the circle with the centre at the origin is not more than 0.45 (Fig. 7). Otherwise, the circle will intersect the curve. This fact reflects the presence of a stability margin equal to 0.45.

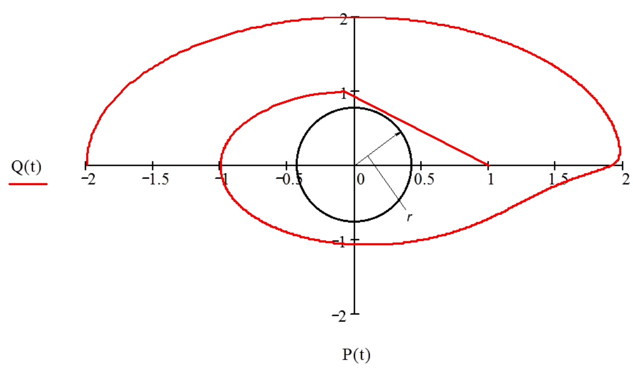



Fig. 7. Determination of the stability margin using the Mikhailov's criterion

In addition, to determine the stability margin, algebraic criteria also can be used. The stability condition for the Hurwitz algebraic criterion is expressed by the inequality, on the right side of which there is zero $(a_{n-1}a_{n-2}-a_{n-3}a_n)>0$. In order to specify a stability margin, it is needed to take a small positive number instead of zero and write it down $(a_{n-1}a_{n-2}-a_{n-3}a_n)>\varepsilon$.

Let us find out the stability margin for the SE EF "Kutuzivka". To do this, we will find a solution of the inequality $(a_4a_5-a_3a_6)>0$ provided that the transition coefficients $K_1K_2K_3K_4$ are unknown. Then we will get:

$$1.366\cdot10^{9}K_1^2K_2^2K_3K_4+1.366\cdot10^{9}K_1^2K_2^2K_3+$$
$$+6.808\cdot10^{10}K_1^2K_2^2+3.632\cdot10^{13}K_1K_2K_3K_4+$$
$$+1.99\cdot10^{12}K_1K_2K_3+2.209\cdot10^{15}K_1K_2+1.1519\cdot10^{19}>0. \quad (8)$$

If we will analyze the coefficients of this inequality, it becomes clear that it is impossible to define separately $K_1$, $K_2$ or even a product $K_1K_2K_3K_4$. However, each term of the inequality includes the coefficients $K_1$ and $K_2$, so we will solve the inequality with respect to the product $K_1K_2$ considering $K_3$ and $K_4$ as constants. After the corresponding transformation, we get:

$$2.771\times10^{13}(K_1K_2)^2+2.765\times10^{25}K_1K_2+$$
$$+1.1519\times10^{19}>0. \quad (9)$$

The roots of the left side of the inequality are:

$$(K_1K_2)_{\mathrm{I}}=1.837\times10^6;\ (K_1K_2)_{\mathrm{II}}=-9.98\times10^{11}. \quad (10)$$

The second root is rejected because the transition coefficient cannot be negative, and the first root represents the limit value of the product of the coefficients $K_1K_2$ at which the system will still be stable: $K_{\mathrm{lim}}=K_1K_2=1.837\times10^6$.

Thus, the inequality $1.837\times10^6>K_1K_2>0$ indicates the condition of the system stability relative to the product $K_1K_2$. In other words, the ratio of supply, demand for goods, overhead, and demand intensity should not exceed $1.837\times10^6$.

Similarly, it is possible to determine the boundary values of all coefficients under the condition of the constancy of others. In turn, the determination of the coefficients limit values when assessing the stability margin allows determining the system stability degree.

Consequently, the proposed complex of models for assessing and analyzing the enterprise operation stability is universal, and with appropriate adaptation, opens up wide opportunities for its use for the PSS study in the conditions of any economy branches in different countries. In particular, a set of models can be used to make managerial decisions in real time in order to ensure stable operation and increase the efficiency of enterprises.

## 7. Conclusions

1. A complex of economic-mathematical models for the enterprise functioning stability estimation and analysis is developed. The mentioned complex includes the structural model of the enterprise constructed using the logistic approach and the ACT apparatus, as well as partial models of the enterprise functional subsystems dynamics.

2. Based on the structural model of the enterprise, due to the transition from the differential equations of dynamics of elements of the system to algebraic ones, as provided by the ACT, a generalized transfer function of the enterprise in a market environment is constructed. The coefficients of the generalized transfer function of the system are determined.

3. Based on the performance indicators of two dairy complexes, the parametrization of the enterprise generalized transfer function was made and scenario models were formed. Using the algebraic Hurwitz criterion and the graph-analytic criterion of Mikhailov, mathematical and simulation models for the study of the enterprise functioning stability dynamics, based on the generalized transfer function of the system, were constructed. By analyzing possible scenarios of operation, these models allow us to investigate the effect of changes in economic indicators on sustainability and to assess the margin of stability.

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