# SCIENCE AND EDUCATION IN THE THIRD MILLENNIUM:

## information technology, education, law, psychology, social sphere, management

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# SCIENCE AND EDUCATION IN THE THIRD MILLENNIUM: Information Technology, Education, Law, Psychology, Social Sphere, Management

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The collective monograph is the result of the generalization of the scientists' conceptual work who study current topics from such fields of knowledge as:  Information Technology, Education, Law, Psychology, Social Sphere, Management through the prism of the possibilities of science and education in the third millennium.

For scientists, educational staff, PhD candidates, masters of educational institutions, university facilities, stakeholders, managers and employees of management bodies at various hierarchical levels and for everyone, who is interested in current problems of Information Technology, Education, Law, Psychology, Social Sphere, Management through the prism of the possibilities of science and education in the third millennium.

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# CHAPTER 2
# INTEGRATED MONITORING AND FORECASTING SYSTEMS FOR CONTINUOUS PRODUCTION

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**Abstract.** The work has developed an integrated system for monitoring and forecasting the flow of continuous technological processes for the final stage of carbon black production, namely the drying process. The purpose of the work is determined: solving the problem of identifying technological processes of continuous production to determine the structure of a dynamic object from the output signal, the structure of its operator based on the structural properties of linear operators and compiling a set of output signals of a continuous technological process. The problems of information recovery for dynamic systems are also outlined. A review of work in the field of identification of systems associated with time series is provided. The technological process for drying granulated carbon black, the limiting values of numerical indicators of the processing process and a list of requirements for the process of automatic stabilization of the temperature of carbon black at the outlet of the drying drum are given. An integrated information system for monitoring and forecasting the state of continuous production has been developed and the mathematical basis for its development is given. The stages of the developed methods for the operator of a dynamic system and the identification and prediction of the state of dynamic systems are determined. A system for monitoring and forecasting the state of continuous production has been implemented in the Python programming language using third-party libraries NumPy, SymPy, matplotlib. Testing of information technology methods for monitoring the technological parameters of the operating mode of a carbon black drying unit was carried out.

**Key words**: carbon black, monitoring and forecasting, continuous production, Hankel matrix, linear operator, factorization of covariance functions.

**Introduction.** Information technology plays an important role in improving the efficiency of continuous technological processes. The development of technologies for determining the presence of a useful signal has reached a level that can significantly increase the efficiency of control systems for complex technological objects by processing experimental data of the output signal to identify and predict the behavior of the control object. Based on this, an important issue is the creation of an integrated monitoring system and forecasting of continuous technological processes, that is, information technology for determining the state of dynamic systems.

The solution to the problems of identifying and predicting the course of continuous technological processes is considered in the article for the production of carbon black, which is one of the typical processes of petrochemical production. The process of obtaining carbon black is associated with the need for strict adherence to technological conditions that ensure its production with standardized parameters. The technological process of drying carbon black is the final stage of its production. One of the main technological characteristics of the process is the temperature regime of the drying unit. Currently, the temperature of granular carbon in drying is controlled by the operator only in one zone in the outlet pipe of the carbon-carbon-gas mixture, relying on his experience.

The problems of information recovery for dynamic systems are considered in many works and are presented as three tasks *(Димова Г.О.[1], 2020):* identification task, when, based on known signals at the input and output of the system, a conclusion is made about the composition of the system and its characteristics; control task, when the characteristics of the system and the input signal are known and the law of change of the signal at the output of the system or the input signal is determined, which at the output leads the system to a given state; measurement task, when the output signal and characteristics of the system are known, the characteristics of the input signal are determined.

For a continuous drying process, there is no information about the input signal and process characteristics, but experimental data on the output signal are known, thus, there is a problem of determining the characteristics of the system and describing the dynamics of the input process. Therefore, it is necessary to develop an integrated monitoring and forecasting system for the continuous process throughout the entire carbon black drying process.

Early work done in the field of system identification associated with time series was based on observing the reactions of controlled objects in the presence of certain control actions and depending on what type of information about the object was used, identification methods were divided into frequency and time *(Sage A. P., Melsa J. L., 1971; Димова Г.О., Ларченко О.В., 2021).* R.E. Kalman presented a description of a controlled system in the form of a state space, which made it possible to work with multidimensional systems.

Methods for identifying systems for control problems were developed and described in the work of B.L. Ho and R.E. Kalman "Effective construction of linear state-variable models from input-output functions" – a subspace method based on the use of projections in Euclidean space, as well as in the work of K.I. Ostrom and T. Bolin "Numerical identification of linear dynamic systems from normal operating records" is a prediction error method based on minimizing a criterion depending on the model parameters. D. Graupe *(Graupe D., 1975)* reviewed a wider class of different identification methods and presented material on the sensitivity of system characteristics to identification errors.

All the considered works relate to three well-known problems of signal theory: identification tasks, control tasks and measurement tasks.

The methods discussed in the monograph by Harry L. Van Trees *(Van Trees H.L., 1971)* are applicable to sequential identification of parameters. The paper examines the relationship between the forms of representation of random processes in a variable state and using the covariance function. The work of Jan C. Willems *(Willems J.C., 1986-1987)* introduced a framework for the study of dynamic systems. The "input-state-output" system approach differs from the usual "input-output" structure in that definitions are made without a priori distinguishing between causes (inputs) and effects (outcomes) and acts as a special type of system view. It is argued that this framework is much better suited to provide a satisfactory conceptual framework for modeling physical systems as a language for mathematical systems theory. These ideas became the basis for the development of an integrated system for use in continuous production.

**1. Characteristics of the continuous technological process for drying carbon black.**

Carbon black is a product consisting of carbon (carbon content about 99%), widely used in the chemical industry as a reinforcing filler in the production of rubbers and plastics. Carbon black is used in the production of automobile tires and rubber products, as well as a component that imparts special properties to plastics, and as a pigment in the paint, polymer, and electrochemical industries. The produced carbon black can correspond to different grades, differing in adsorbing properties, pH value, ash content, sulfur content, granule strength, bulk density, dust content.

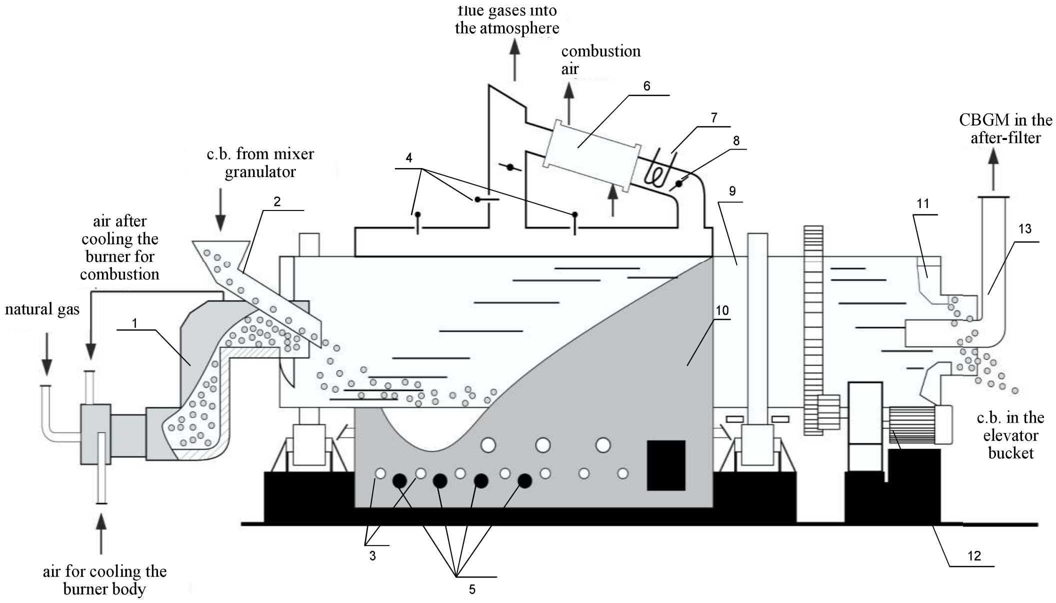
The technological process for producing carbon black includes the following production stages:

- the process of preparing the raw mixture and submitting it to production;
- the process of producing carbon black in chemical reactors;
- the process of capturing carbon black and transporting it to the processing site;
- process of wet granulation and drying of carbon black;
- carbon black packaging process.

Granulation is the production of granules of relatively uniform size and density from bulk materials *(Димова Г.О., 2020).* There are two main methods for granulating carbon black - dry and wet. In the Public Joint Stock Company "Kremenchug Carbon Black Plant" granulation is carried out using the wet method, that is, by mixing fine carbon powder with a heated water-molasses solution in a rotary granulator. Carbon black granules then require drying to remove excess moisture and acquire the desired physical properties. Thus, the technological process of drying granulated carbon black is the final stage of its production.

Drying is an energy-intensive process that significantly affects the quality of the output product. The drying process is carried out in modified drum furnaces operating in a very intense mode, and occurs due to the supply of heat from the flue gases of the axial gas burner and the supply of heat from the liquid fuel and gas burners of the furnace through the walls of the drum. The diagram of the drying drum, the location of the burners and temperature control points are shown in Figure 1.

Currently, there is no possibility of direct measurements of the temperature of granular carbon moving along the drum from the loading end to unloading. The drying process is characterized by a nonlinear kinetic dependence and a changing mass of material in different parts of the drum, which makes it difficult to control the process and reduces the accuracy of stabilizing the temperature of the output product.




1 – axial burner gases,
2 – wet carbon black loading port,
3 – gas-burners,
4 – flue gas monitoring thermocouples,
5 – liquid fuel burners,
6 – combustion air heating heat exchanger,
7 – spray air heat exchanger,
8 – adjusting latch,
9 – drum dryer (DD),
10 – combustion chamber,
11 – buckets for unloading dry carbon black (c.b.),
12 – motor-gear group,
13 – outlet pipe for carbon-black-gas mixture (CBGM)

Figure 1 – Process installation – drying drum

The limit values of individual numerical indicators of the carbon black processing process are given in Table 1.

Table 1 – List of numerical indicators of the technological process

| No. | Indicator name | Numerical value |
|---|---|---|
| 1 | Loading onto the granulator by water, kg/h | 500 – 5000 |
| 2 | Concentration of molasses in water-molasses solution based on dry substances, % not more than | 1,5 |
| 3 | Water pressure at the inlet to the mixer-granulator, kg/cm$^2$ | 2 – 8 |
| 4 | Temperature of water supplied to the mixer-granulator, ºC | 60-90 |

| | | |
|---|---|---|
| 5 | Mass fraction of moisture at the outlet of the mixer-granulator, % | 40 – 55 |
| 6 | Natural gas pressure in front of the furnace burners, kg/cm$^2$, not lower | 1,3 |
| 7 | Temperature of gases at the outlet of the drying drum, ºC | 120 – 250 |
| 8 | Temperature of gases in the 1st zone of the drying drum furnace, ºC, not more | 780 |
| 9 | Temperature of gases in the chimney, ºC, not more | 650 |
| 10 | Temperature of carbon black at the outlet of the drying drum, °C, not more | 115 – 200 |
| 11 | Temperature of carbon black at the entrance to the finished product bunker, ºC, not more | 85 |
| 12 | Mass fraction of water after the drying drum, %, not more | 0,9 |
| 13 | Vacuum in the drying drum, mm water. col (Pa), not lower | 2 (19,6) |
| 14 | Vacuum in the surge tank, mm water. col (Pa), not lower | 10 (98) |

The process of automatically stabilizing the temperature of carbon black at the outlet of the drying drum has a significant impact on the final quality of the product. When developing software, you should adhere to the requirements listed below (Table 2).

Table 2 – List of requirements for the process of automatic stabilization of the temperature of carbon black at the outlet of the drying drum.

| No. | Requirement | Name / Numerical value |
|---|---|---|
| 1 | Minimum temperature of carbon black granules at the outlet of the drying drum, °C | 115 |
| 2 | Maximum temperature of carbon black granules at the outlet of the drying drum, °C | 190 |
| 3 | Desirable temperature range of carbon black granules at the outlet of the drying drum, °C | 140-160 |
| 4 | Model calculation of the state of a continuous technological process for each measurement zone | calculation |
| 5 | Formation of a forecast of carbon black temperature for a time, s, not less | 600 – 1200 |

Temperature measurements were carried out at the following points in the process flow diagram:

– carbon-gas mixture at the drum outlet;
– dry granular carbon at the drum outlet;
– in the upper part of the firebox in the 1st zone;
– in the upper part of the firebox in the 2nd zone;
– in the upper part of the firebox in the 3rd zone.

Data analysis and obtaining numerical indicators of the control process were carried out using instantaneous values of technological process parameters obtained with an interval of 1 second (without averaging). The results of recording instantaneous values of parameters of a continuous technological process are presented graphically in Fig. 2.

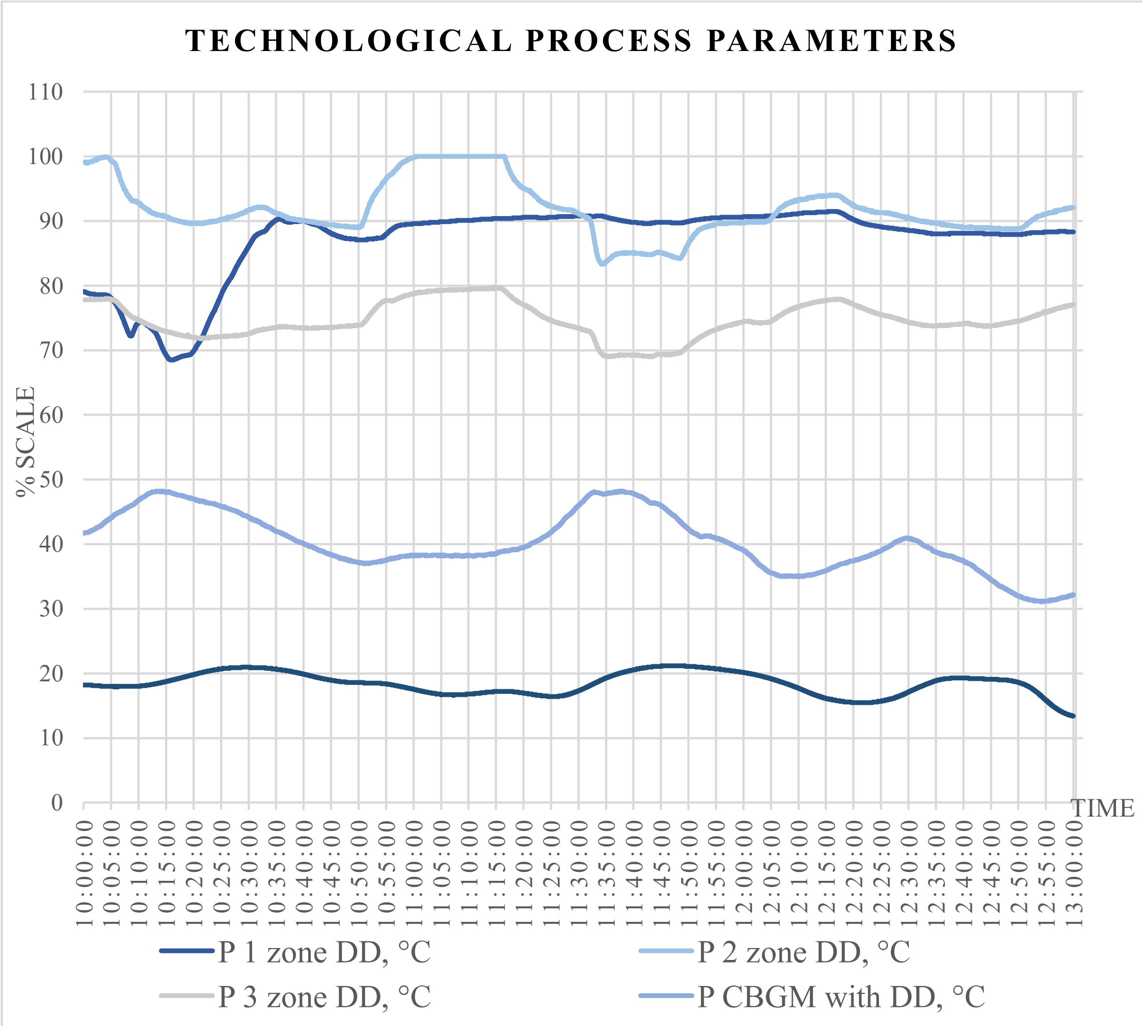



Figure 2 – Results of recording instantaneous values of technological process parameters obtained during the experiment

Monitoring of these zones allows you to instantly respond to changes and stabilize the temperature, so as not to bring the carbon black drying process to critical situations.

**2. Mathematical basis for developing a system for monitoring and forecasting the state of continuous production.**

To implement methods for monitoring and predicting the course of continuous technological processes, it is necessary to develop software based on the method of organizing experimental data using Hankel forms and matrices and methods for modeling the operator of a dynamic system and factorizing covariance functions that allow solving inverse problems of dynamics.

An integrated system for monitoring and forecasting the state of continuous production is shown in Fig. 3, where all information processes are represented by blocks that have information inputs, control outputs, execution regulations determined by methods and models *(Димова Г.О., Димов В.С., 2019)*.

The upper blocks correspond to the implementation of the method for finding the operator of a dynamic system model, the lower ones - to solving the direct problem (obtaining libraries of models), the middle ones - to solving the inverse problem using the factorization method of covariance functions. Let's consider the main points of each of the methods of building this information system.

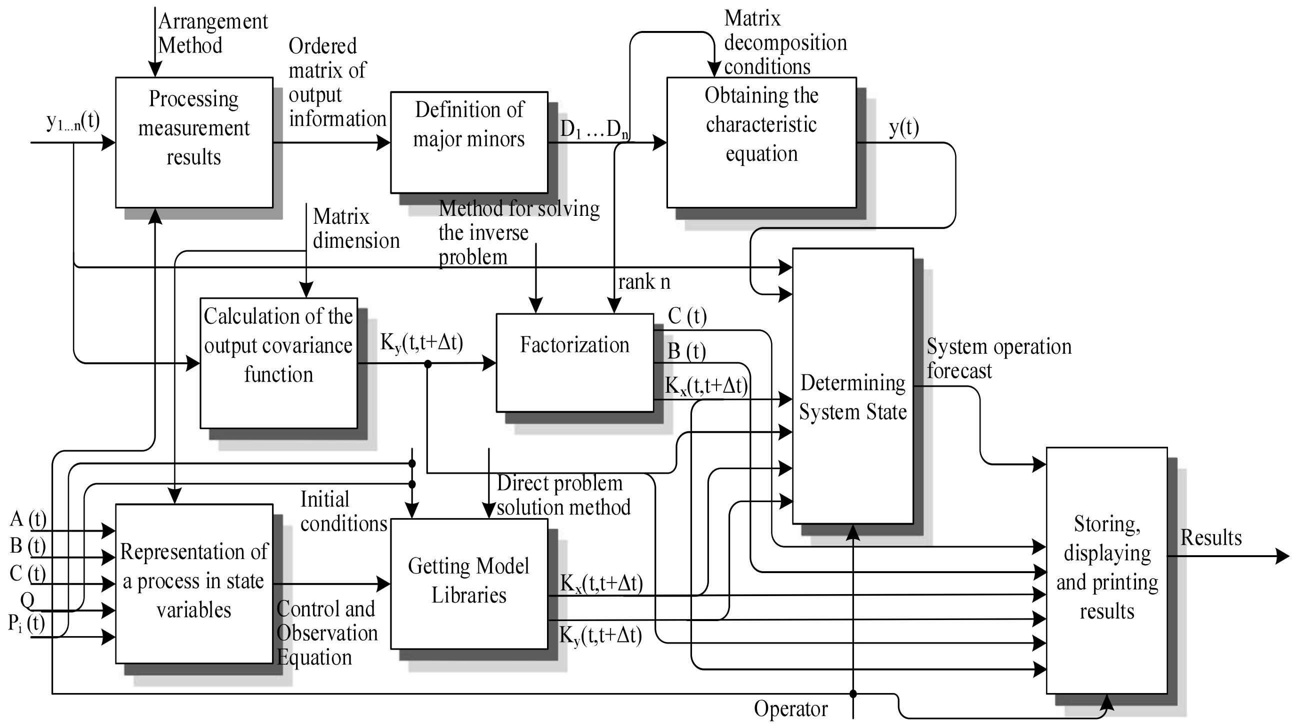



Figure 3 – Integrated system for monitoring and forecasting the state of continuous production

*1. Method for finding the operator of a dynamic system model.*

The solution to the problem of analyzing the structure of a continuous technological process for the production of carbon black was implemented by two methods: taking into account the stochastic approach to the analysis of output signals and without taking into account the random components of the output signal based on linear reflections of a set of linear spaces, that is, a set-theoretic approach. In the first approach, the characteristic polynomial of the operator of the model of a dynamic object is determined, in the second – a representation in the form of an operator of the model "input-state space-output" *(Димова Г.О., 2020).*

The output signal $\mathbf{y}_o(t)$ of an autonomous object is described by the usual $l$- th order differential equation *(Марасанов В.В., Димова Г.О., 2017; Димова Г.О., 2022):*

$$\frac{d^m \boldsymbol{y}_o(t)}{dt^m} + \sum_{l=0}^{m-1} a_m \frac{d^m \boldsymbol{y}_o(t)}{dt^m} = 0, \quad (1)$$

with initial conditions $\left\{\frac{d^m \boldsymbol{y}_o(0)}{dt^m}\right\}, \quad m = 0,1,2,\ldots,m-1.$

If equation (1) has no multiple roots, we obtain the solution $\mathbf{y}_o(t) = \sum_{i=1}^{m} \mathbf{C}_i \, exp(r_i t), \quad t \leq 0$. Characteristic polynomial of equation (1)

$$a_m r^m + a_{m-1} r^{m-1} + \cdots + a_1 r + a_0 = 0, \quad (2)$$

where $r_i$ are the roots of equation (1).

Equation (2) displays the structure of linear operator (1) and establishes the relationship between the set of roots $r_i$ and the vector of coefficients $(a_0, a_1, \ldots, a_m)$.

Calculate coefficients $a_i$ from records $\mathbf{Y}_0(t)$ *(Гамецкий А.Ф., Соломон Д.И., 1997).*

To obtain estimates of the coefficients of the characteristic polynomial (equation

(2)) and determine its order, it is necessary to perform the following operations:

1) Find : 1-st differences $u_i^{(1)} = y_i - y_{i-1}$

2-nd differences $u_i^{(2)} = u_i^{(1)} - u_{i-1}$

...

$k$-th differences $u^{(k)} = u_i^{(k-1)} - u_{i-1}^{(k-1)}$.

2) For all difference series, having previously checked them for the fulfillment of the Gauss-Markov conditions, find their variances:

– for the output smoothed series;

– difference series of $k$-th order ($k$ = 1, 2, …).

3) Determine the order of the regression equation, if this value does not exceed the specified accuracy of the analog-to-digital converter, then $m = k - 1$ determines the order of the differential operator (1) and the corresponding regression equations

$$\hat{\mathbf{y}}_t = a_0 + a_1 t + \cdots + a_m t^m.$$

Assessing the structure of a dynamic operator model is reduced to assessing the structure of its characteristic polynomial. Calculation of the roots of the characteristic polynomial based on the Lobachevsky-Greffe method allows us to assess the stability of the model of the structure of a dynamic object *(Димова Г.О.[11], 2020; Dymova H., Larchenko O., 2023).*

A method has been developed for finding the structure of an operator of a dynamic object from its output signals based on the structural properties of linear operators and compiling a set of output signals, representing them in the form of Hankel forms and Hankel matrices. Requirements for the model have been formed.

To obtain a model of the form "input – state – output", a state space model (**A**, **B**, **C**, **D**) is considered, where **A** is the matrix of system coefficients, **B** is the control matrix, **C** is the output matrix, **D** is the bypass matrix *(Димова Г.О., 2022).*

As a result of processing the output signals, $2n - 1$ numbers or vectors were obtained $s_0, s_1, \dots, s_{2n-2}$. A symmetric Hankel matrix has been compiled, which has the form *(Гантмахер Ф.Р., 2015):*

$$\mathbf{S} = ||s_{i+k}||_0^{n-1} = \left\| \begin{matrix} s_0 & s_1 & s_2 & \cdots & s_{n-1} \\ s_1 & s_2 & s_3 & \cdots & s_n \\ s_2 & s_3 & s_4 & \cdots & s_{n+1} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ s_{n-1} & s_n & s_{n+1} & \cdots & s_{2n-2} \end{matrix} \right\|$$

To consider the issue of decomposition of Hankel matrices and obtain a representation of the model in the state space (**A**, **B**, **C**, **D**), let's move from the matrix **S** to the matrix $\mathrm{A} = ||\mathrm{a}_{ik}||_1^n$ ($i$ = 1, 2, …, $m$; $k$ = 1, 2, …, $n$), of the same dimension. This matrix will be decomposed if it can be reduced to the form

$$\widetilde{\mathbf{A}} = \left\| \begin{matrix} \mathbf{B} & 0 \\ \mathbf{C} & \mathbf{D} \end{matrix} \right\|, \tag{3}$$

where **B** and **D** are square matrices *(Lancaster P., 1969; Димова Г.О., 2022).*

This is possible if and only if some partition of all its indices 1, 2, ..., $n$ into two additional systems (without common indices) is possible $i_1$, $i_2$, ..., $i_\mu$; $k_1, k_2, ..., k_\nu$ ($\mu + \nu = n$) $a_{i_\alpha k_\beta} = 0$ ($\alpha = 1, 2, \ldots, \mu$; $\beta = 1, 2, \ldots, \nu$). Otherwise, matrix **A** will be indecomposable. By permutation of rows in a square matrix $\mathrm{A} = ||a_{ik}||_1^n$ we mean the connection of permutations of rows with the same permutation of columns of matrix **A**. The permutation of rows corresponds to the renumbering of the basis vectors, that is, the transition from the $\vec{e}_1, \vec{e}_2, \ldots, \vec{e}_n$ basis to the new $\vec{e}_1' = \vec{e}_{j1}, \vec{e}_2' = \vec{e}_{j2}, \ldots, \vec{e}_n' = \vec{e}_{jn}$, basis, where ($j1, j2, \ldots, jn$) is some permutation of the indices 1, 2, ..., $n$. In this case, matrix **A** goes into a similar matrix $\widetilde{\mathrm{A}} = \mathrm{T}^{-1}\mathrm{AT}$, **T** is some non-singular matrix *(Марасанов В.В., Димова Г.О., 2017; Димова Г.О., 2022).*

By $\nu$-dimensional coordinate subspace in **R** we mean any subspace in **R** with basis $\vec{e}_{k_1}, \vec{e}_{k_2}, \ldots, \vec{e}_{k_\nu}$ ($1 \le k_1 < k_2 < \ldots < k_\nu \le n$). The matrix $\mathrm{A} = ||\mathrm{a}_{ik}||_1^n$ can be decomposed if and only if the operator **A** corresponding to this matrix has a $\nu$-dimensional invariant coordinate subspace of $\nu < n$. Consequently, by rearranging the rows, matrix **A** can be represented in the form (3) and, if $|\mathbf{A}| \ge 0$ and in the characteristic determinant any of the main minors turns to zero, then matrix **A** will be decomposed.

A system with state space is a quadruple $\Sigma_i = \{T, W, X, B_i\}$, where $T \subset R$ is a set of time moments; $W$ – alphabet of external signals; $X$ – state space; $B_i \subset (W \times X)^T$ – set of internal states.

It is assumed that $B_i$ satisfies the state axiom

$$\{(\vec{w}_k, \vec{x}_k) \in B_i, k = 1,2, t_0 \in T, \vec{x}_1(t_0) = \vec{x}_2(t_0)\} \to \{\vec{w}_1, \vec{x}_1 \underset{t_0}{\wedge} (\vec{w}_2, \vec{x}_2) \in B_i\},$$

where $\vec{w}_k$ – vectors of output signals of a dynamic object; $\underset{t_0}{\wedge}$ – concatenation sign.

System

$$\begin{aligned} \sigma\vec{x} &= \mathbf{A}'\vec{x} + \mathbf{B}'\vec{u} \\ \vec{w} &= \mathbf{C}'\vec{x} + \mathbf{D}'\vec{u} \end{aligned} \quad (4)$$

defines a dynamic system with state space, in which $\sigma$ is the time displacement operator, $T = Z_+$ or $Z$ is a set of time moments (discrete or continuous), $Z \ge 0$.

$W = R^q, X = R^n$ i $B'(\mathbf{A}', \mathbf{B}', \mathbf{C}', \mathbf{D}') := \{(\vec{w}, \vec{x}): T \to R^q \otimes R^n | \exists \vec{u}: T \to R^m$, such that it is carried out (4)$\}$. External behavior of the system – $B_S(\mathbf{A}', \mathbf{B}', \mathbf{C}', \mathbf{D}')$. $R$ – number axis (quantized or continuous); $R^q$, $R^n$, $R^m$ – corresponding $q$, $n$, $m$-dimensional linear spaces; sign": = " – equal by definition; ⊗ – Cartesian product of sets *(Гантмахер Ф.Р., 2015; Димова Г.О., 2022).*

The formulated problem: for obtained as a result of processing observations of a dynamic object the $q$-dimensional time series $\vec{w}(t_0), \vec{w}(t_0 + 1), \ldots, \vec{w}(t_1)$ $(-\infty \le t_0 \le t \le t_1 \le \infty)$ from $\vec{w}(t) \in R^q$ find a dynamic model of the object that explains the above observations.

The output signals of the dynamic object $\vec{w}(t)$ after processing by the measuring system will be multidimensional time series: $\vec{w}\ (0), \vec{w}\ (1), \ldots, \vec{w}\ (t), \ldots$ in the 1st case for $T = Z_+$ and $\ldots, \vec{w}\ (-1), \vec{w}\ (0), \vec{w}\ (1), \ldots, \vec{w}\ (t), \ldots$ in case 2 for $T = Z$.

Based on the above, infinite (vector) Hankel matrices or a Hankel matrix divided into blocks for the series $\vec{w}(t)$: $Z \to R^q$

$$\begin{pmatrix} H_-(\vec{w}) \\ H_+(\vec{w}) \end{pmatrix} := \begin{pmatrix} \dots & \vdots & \vdots & \dots & \vdots & \dots \\ \dots & \vec{w}(-t-1) & \vec{w}(-t) & \dots & \vec{w}(0) & \dots \\ \dots & \vdots & \vdots & \dots & \vdots & \dots \\ \dots & \vec{w}(t-2) & \vec{w}(-1) & \dots & \vec{w}(t'-1) & \dots \\ \dots & \vec{w}(-1) & \vec{w}(1) & \dots & \vec{w}(t') & \dots \\ \dots & \vec{w}(0) & \vec{w}(1) & \dots & \vec{w}(t'+1) & \dots \\ \dots & \vdots & \vdots & \dots & \vdots & \dots \\ \dots & \vec{w}(t-1) & \vec{w}(t) & \dots & \vec{w}(t+t') & \dots \\ \dots & \vdots & \vdots & \dots & \vdots & \dots \end{pmatrix}. \quad (5)$$

The structure is determined in the matrix (5) $H(\vec{w})$. To do this, the matrices $H_-$ and $H_+$ are introduced (where $H_-$ is composed of rows of the matrix $H_-(\vec{w})$, and $H_+$ is composed of rows of the matrix $H_+(\vec{w})$), which is $\text{rank}(H_-; H_+) = \text{rank}$ $(\text{H}_-(\vec{w});\ H_+(\vec{w})) =: n$.

Lagging detected. From the Hankel structure it follows that for $t \in Z_+$ the expression

$$\rho_t := \text{rank H}_t(\vec{w}) - \text{rank H}_{t-1}(\vec{w}),$$
$$\rho_0 := \text{rank H}_0(\vec{w})$$

define a non-increasing sequence of non-negative integers.

Next, we calculate such a $t'$ that $\rho_t = \rho_{t'}$ for $t > t'$.

Matrix defined $\text{col}(\text{H}_1, \text{H}_2) = \begin{pmatrix} \text{H}_1 \\ \text{H}_2 \end{pmatrix}$

The state space is determined: the kernel (*ker*) of the matrix $H_1$ is calculated and $H = \text{H}_2\, ker\, H_1$ is assumed, where *ker* is the kernel (space zero) of the linear mapping.

The space of input signals is defined. It is assumed that $\vec{f}(t) := \text{col}\ (\vec{w}(t), \vec{x}(t))$ and $S := \text{span}\ \{\vec{f}(t), t \in Z\}$. It is obvious that the projection $\pi_x$: $S \to X$, defined by the equality $\pi_x \vec{f}(t) := \vec{x}(t)$, is surjective (thus $S$ is represented as a vector bundle over $X$).

Given a vector space $U$ and a surjective reflection $\pi_u := S \to U$, so that $S = \text{X} \oplus U$, that is, so that the reflection $\pi := (\pi_x, \pi_u)$ is bijective. It is obvious that $U = dim\, U = dim\, S - dim\, X$ (dim is the dimension of linear space). Let us assume $\vec{u}(t) = P_u \vec{f}(t)$, where $P_u$ is the projection operator.

System parameters have been determined. For $i \in (n+m)$, numbers $t_i$ are introduced such that the vectors $\vec{f}(t_i)$ form the basis of the space $S$. Then $\vec{f}(t_i) = \text{col}(\vec{x}(t_i), \vec{u}(t_i))$ will also be a basis for $\text{X} \oplus U$. Now we have defined such an
$(n+q) \times (n+m)$- matrix **M**, that

$$\mathbf{M}: \begin{pmatrix} \vec{x}(t_i) \\ \vec{u}(t_i) \end{pmatrix} \to \begin{pmatrix} \vec{x}(t_i+1) \\ \vec{w}(t_i) \end{pmatrix}.$$

As a result, $\vec{w}$: $Z \to R^q$ is accepted – the observed time series and $\mathbf{M} \in R^{(n+q)\times(n+m)}$ – a matrix is constructed, and dividing it into blocks we have

$$\mathbf{M} := \begin{pmatrix} \mathbf{A}' & \mathbf{B}' \\ \mathbf{C}' & \mathbf{D}' \end{pmatrix}.$$

so $\mathbf{A}' \in R^{n \times n}$, $\mathbf{B}' \in R^{n \times m}$, $\mathrm{C}' \in R^{q \times n}$ i $\mathbf{D}' \in R^{q \times m}$. Then the system $\Sigma_S(\mathbf{A}', \mathbf{B}', \mathbf{C}', \mathbf{D}')$ is the strongest irrefutable model with the minimum state space and the minimum number of inputs for the time series $\vec{w}$.

The method of modeling the operator of a dynamical system based on the properties of linear operators and ordering experimental data using Hankel quadratic forms and matrices allows one to solve inverse problems of dynamics at the set-theoretic level mathematically in an exact and consistent formulation. This leads to the concept of an optimal accurate model (ignoring noise), namely the strongest irrefutable model in the class of linear systems. The stages of the method are shown in Fig. 4.

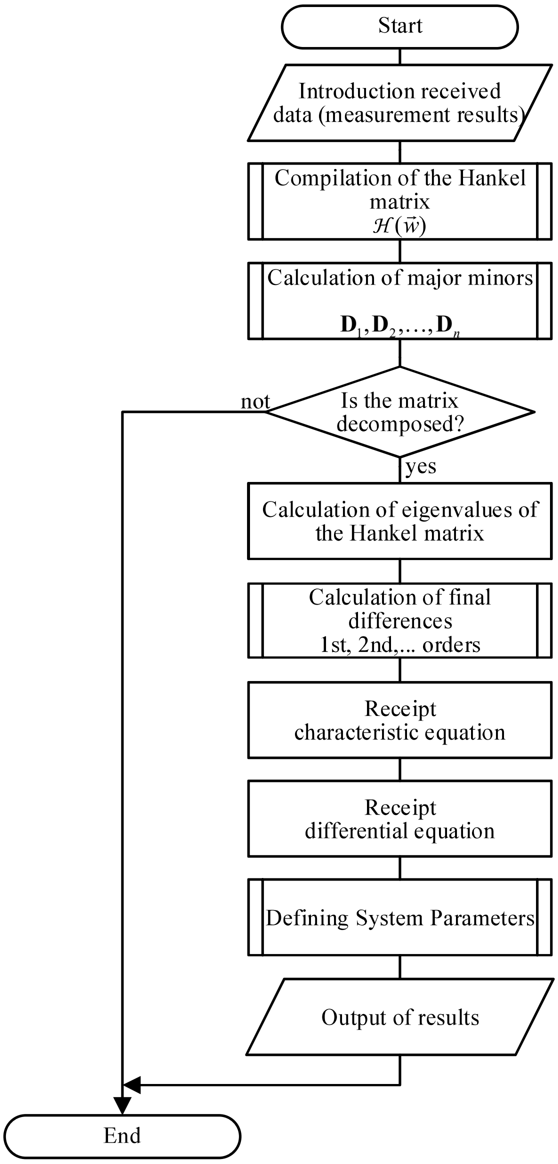



Figure 4 – Stages of the dynamic system operator modeling method

The sequence of constructing a model of an operator of a linear dynamic system as a solution to the inverse problem of dynamics – to determine the structure of the operator in the state space from the output signal – allows us to develop information technologies for real dynamic systems in a linear approximation.

*2. Solving direct and inverse problems using the factorization method of* *covariance functions.*

The linear representation of a random process in state variables is determined by five matrices: $\mathbf{A}(t)$ – matrix of the system state with dimension $(n \times n)$; $\mathbf{B}(t)$ – control (input) matrix with dimension $(n \times p)$; $\mathbf{C}(t)$ – measurement matrix with dimension $(m \times n)$; $\mathbf{Q}$ – covariance matrix of vector white excitation noise; $\mathbf{P}_i(t)$ – cross-correlation matrix between the input of the message source and the additive noise in the channel and the system of equations with given initial conditions *(Димова Г.О.[1], 2020; Dymova H., 2021):*

$$\frac{d\vec{x}}{dt} = \mathbf{A}(t)\,\vec{x}(t) + \mathbf{B}(t)\,\vec{u}(t),\ T_i \le t, \tag{6}$$

$$\vec{y}(t) = \mathbf{C}(t)\,\vec{x}(t),\ T_i \le t, \tag{7}$$

where $\vec{x}(t)$ – state vector with dimension $(n\times1)$; $\vec{u}(t)$ is a white exciting process with dimension $(p\times1)$, has a covariance function of the form $E[\vec{u}(t)\,\vec{u}^T(\tau)] = \mathbf{Q}\,\delta(t-\tau)$, where $E$ is the operator mathematical expectation; $\vec{y}(t)$ – observed process with dimension $(m\times1)$. Equation (6) is a linear equation of state, and (7) is an observation equation.

The procedure for finding the covariance function of the original process $\mathbf{K}_y(t,\tau)$ consists of three stages *(Van Trees H.L., 1971):*

1) from equation (7) one can discover the connection between the covariance function of the output process $\mathbf{K}_y(t,\tau)$ and the covariance matrix $\mathbf{K}_x(t,\tau)$ of the state vector $\vec{x}(t)$:

$$\mathbf{K}_y(t,\tau) = \mathbf{C}(t)\,\mathbf{K}_x(t,\tau)\mathbf{C}^T(\tau); \tag{8}$$

2) the covariance matrix of the input process $\mathbf{K}_x(t,\tau)$ under initial conditions $E[\vec{x}(T_i)\,\vec{x}^T(T_i)] = \mathbf{K}_x(T_i,T_i) = \mathbf{P}_i$, satisfies the differential equation:

$$\dot{\mathbf{K}}_x(t,\tau) = \mathbf{A}(t)\,\mathbf{K}_x(t,t) + \mathbf{K}_x(t,t)\,\mathbf{A}^T(t) + \mathbf{B}(t)\,\mathbf{Q}\,\mathbf{B}^T(t); \tag{9}$$

3) due to the uncorrelatedness of $\vec{u}(t')$ and $\vec{x}(t)$ on the integration interval of the differential equation (9), we obtain:

$$\mathbf{K}_x(t,\tau) = \begin{cases} \mathbf{\Theta}(t,\tau)\,\mathbf{K}_x(\tau,\tau),\ t \ge \tau \\ \mathbf{K}_x(t,t)\,\mathbf{\Theta}^T(\tau,t),\ \tau \ge t' \end{cases}$$

where $\mathbf{\Theta}(t,\tau)$ is the transition matrix obtained from the differential equation $\dot{\mathbf{\Theta}}(t,t_0) = \mathbf{A}(t)\,\mathbf{\Theta}(t,t_0)$, under the initial condition $\mathbf{\Theta}(t_0,t_0) = \mathbf{I}$, where $\mathbf{I}$ is the unit matrix.

All stationary processes can be modeled using systems with constant parameters if the covariance matrix of the initial state is chosen appropriately. The solution to the direct problem is to find the covariance function $\mathbf{K}_y(t,\tau)$. The transition matrix is determined by the matrix exponential factor $\mathbf{\Theta}(t,\tau) = e^{\mathbf{A}(t-\tau)}$. For the matrix $\mathbf{K}_x(t,\ t+\Delta t)$ to be a function of only $\Delta t$, the matrix $\mathbf{K}_x(t,\ t)$ must be equal to the constant value $\mathbf{P}_\infty$, which is a stationary solution to the differential equation (9). Consequently, segments of the stationary process are modeled using systems with constant parameters and setting the covariance matrix of the initial state $\mathbf{P}_i$ and equal to $\mathbf{P}_\infty$. The solution to equation (9) has the form (Dymova H., 2021):

$$\mathbf{P}_\infty = \int_0^\infty e^{\mathbf{A}t}\mathbf{B}\,\mathbf{Q}\,e^{\mathbf{A}^T t}dt = \frac{1}{2\pi j}\int_{-j\infty}^{j\infty}[\mathbf{I}s-\mathbf{A}]^{-1}\mathbf{B}\,\mathbf{Q}\,\mathbf{B}^T[-\mathbf{I}s-\mathbf{A}^T]^{-1}ds.$$

State vector covariance matrix

$$\mathbf{K}_x(t, t+\Delta t) = \begin{cases} e^{-\mathbf{A}\Delta t}\mathbf{P}_\infty, & \Delta t \le 0, \\ \mathbf{P}_\infty e^{\mathbf{A}\Delta t}, & \Delta t > 0. \end{cases}$$

According to formula (8)

$$\boldsymbol{K}_y(t, t+\Delta t) = \begin{cases} \boldsymbol{C}(t)\, e^{-A\Delta t}\boldsymbol{P}_\infty \boldsymbol{C}^T(t), & \Delta t \le 0, \\ \boldsymbol{C}(t)\, \boldsymbol{P}_\infty e^{A^T\Delta t}\boldsymbol{C}^T(t), & \Delta t > 0. \end{cases}$$

that is, the correlation function of the system's output is expressed in terms of the system's state variables. So, there is an inverse problem: knowing the correlation matrix of the output for given $\mathbf{C}(t)$ and $\mathbf{P}_\infty = const$, determine the structure of the transfer function of the system, that is, solve the problem of partial identification of the system.

Covariance matrix of the system output $\vec{\mathbf{y}}(t) - \mathbf{K}_y(t,\tau)$, constructed based on the observation of a random output process $\vec{\mathbf{y}}(t)$ measured by a device with an observation matrix $\mathbf{C}(t)$ on the interval $T_i \le t,\ \tau \le T_j$. For the process $\vec{\mathbf{y}}(t)$ under consideration, we use its description in state variables, for which it is necessary to find the matrices $\mathbf{A}(t)$, $\mathbf{B}(t)$, $\mathbf{C}(t)$, $\mathbf{Q}$ and $\mathbf{P}_i$, that is, solve the problem of factorization of the covariance function. The only way to take into account the possible nonstationarity of the system's output process is factorization in the time domain.

Solving the inverse problem consists of three stages *(Dymova H., 2021):*

1) We limit the class of these systems to only systems with matrix triplets $(0, \mathbf{B}(t), \mathbf{C}(t))$.

2) We derive the differential equation $\mathbf{K}_{x^*}(t, t)$ through the derivatives of the matrices $\mathbf{F}(t)$ and $\mathbf{G}(t)$.

$$\mathbf{K}_y(t,\tau) = \begin{cases} \mathbf{F}^T(t)\,\mathbf{G}(\tau), & t \ge \tau, \\ \mathbf{G}^T(t)\,\mathbf{F}(\tau), & \tau \ge t, \end{cases}$$

where $\mathbf{F}^T(t) = \mathbf{C}(t)\,\mathbf{\Theta}(t, t_1)$, $\mathbf{G}(t) = \mathbf{\Theta}(t_1, t)\,\mathbf{K}_x(t,t)\,\mathbf{C}^T(t)$, $t_1$ is an arbitrary time variable in the domain definition of the process $\vec{\mathbf{y}}(t)$.

3) The solution to the factorization problem $(0, \mathbf{B}(t), \mathbf{C}(t))$ and $(\mathbf{Q}, \mathbf{P}_i(t))$ can be expressed in terms of $\mathbf{K}_{x^*}(t, t)$ and the derivatives of the matrices $\mathbf{F}(t)$ and $\mathbf{G}(t)$. As a result, we obtain a description of a random process in variables of states. To do this, we arrange the components $\mathbf{K}_y(t, \tau)$ in the reverse order of differentiation (Fig. 5).

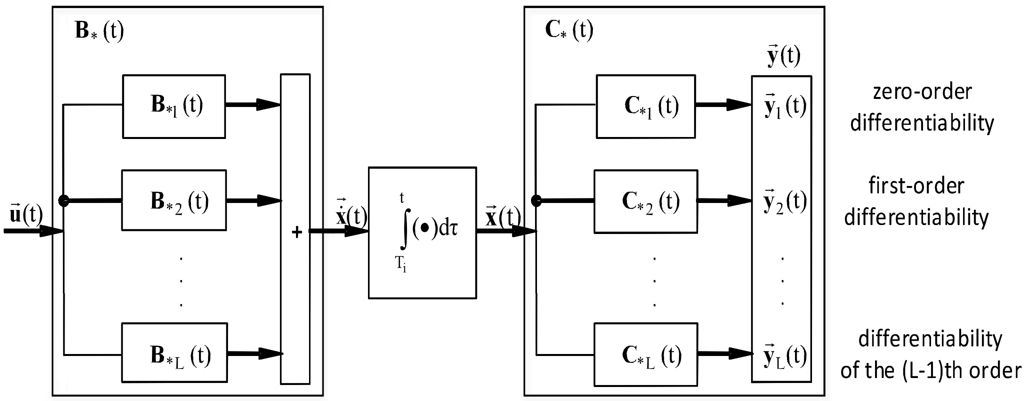



Figure 5 – Structural scheme of the implementation of the output process in accordance with the its components differentiability *(Dymova H., 2021)*

We identify $\mathbf{C}(t)$ with the transposed $\mathbf{F}(t)$ $\mathbf{C}_{*l}^T(t) = \mathbf{F}_l(t)$, we obtain

$\mathbf{G}_l(t) = \mathbf{K}_{x_*}(t,t)\,\mathbf{F}_l(t)$. After differentiating $\mathbf{F}(t)$ and $\mathbf{G}(t)$ and determining the initial conditions, we obtain a matrix equation of dimension $(r_l \times r_l)$

$$\left(\mathbf{C}_{*l}^{(l-1)}(t)\mathbf{B}_*(t)\right)\left(\mathbf{B}_*^T(t)\mathbf{C}_{*l}^{(l-1)T}(t)\right) =$$
$$= \mathbf{F}_l^{(l-1)\mathrm{T}}(t)\,\mathbf{G}_l^{(l)}(t) - \mathbf{G}_l^{(l-1)T}(t)\,\dot{\mathbf{F}}_l^{(l)}(t) = \mathbf{D}_l(t)\ ,$$
$$\mathbf{B}_{*l}(t) = \left(\mathbf{G}_l^{(l)}(t) - \mathbf{K}_{x_*}(t,t)\,\mathbf{F}_l^{(l)}(t)\right)\left[\mathbf{D}_l^{-\frac{1}{2}}(t)\right]^T$$

and define a differential equation for $\mathbf{K}_{x*}(t, t)$, which is essentially a Riccati-type differential equation

$$\dot{\mathbf{K}}_{x_*}(t,t) = \Big\{\left[\mathbf{G}_1^{(1)}(t)\quad \mathbf{G}_2^{(2)}(t)\quad \cdots\quad \mathbf{G}_L^{(L)}(t)\right] -$$
$$-\mathbf{K}_{x_*}(t,t)\left[\mathbf{F}_1^{(1)}(t)\quad \mathbf{F}_2^{(2)}(t)\quad \cdots\quad \mathbf{F}_L^{(L)}(t)\right]\Big\} \times$$
$$\times \begin{bmatrix} \mathbf{D}_1(t) & 0 & \cdots & 0 \\ 0 & \mathbf{D}_2(t) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{D}_L(t) \end{bmatrix}^{-1} \times \qquad (10)$$
$$\times \Big\{\left[\mathbf{G}_1^{(1)}(t)\quad \mathbf{G}_2^{(2)}(t)\quad \cdots\quad \mathbf{G}_L^{(L)}(t)\right] -$$
$$-\mathbf{K}_{x_*}(t,t)\left[\mathbf{F}_1^{(1)}(t)\quad \mathbf{F}_2^{(2)}(t)\quad \cdots\quad \mathbf{F}_L^{(L)}(t)\right]\Big\}\ .$$

For the created mathematical model for predicting changes in the state of dynamic systems over time, a method for identifying and predicting the state of dynamic systems has been developed. The stages of the method are shown in Fig. 6.

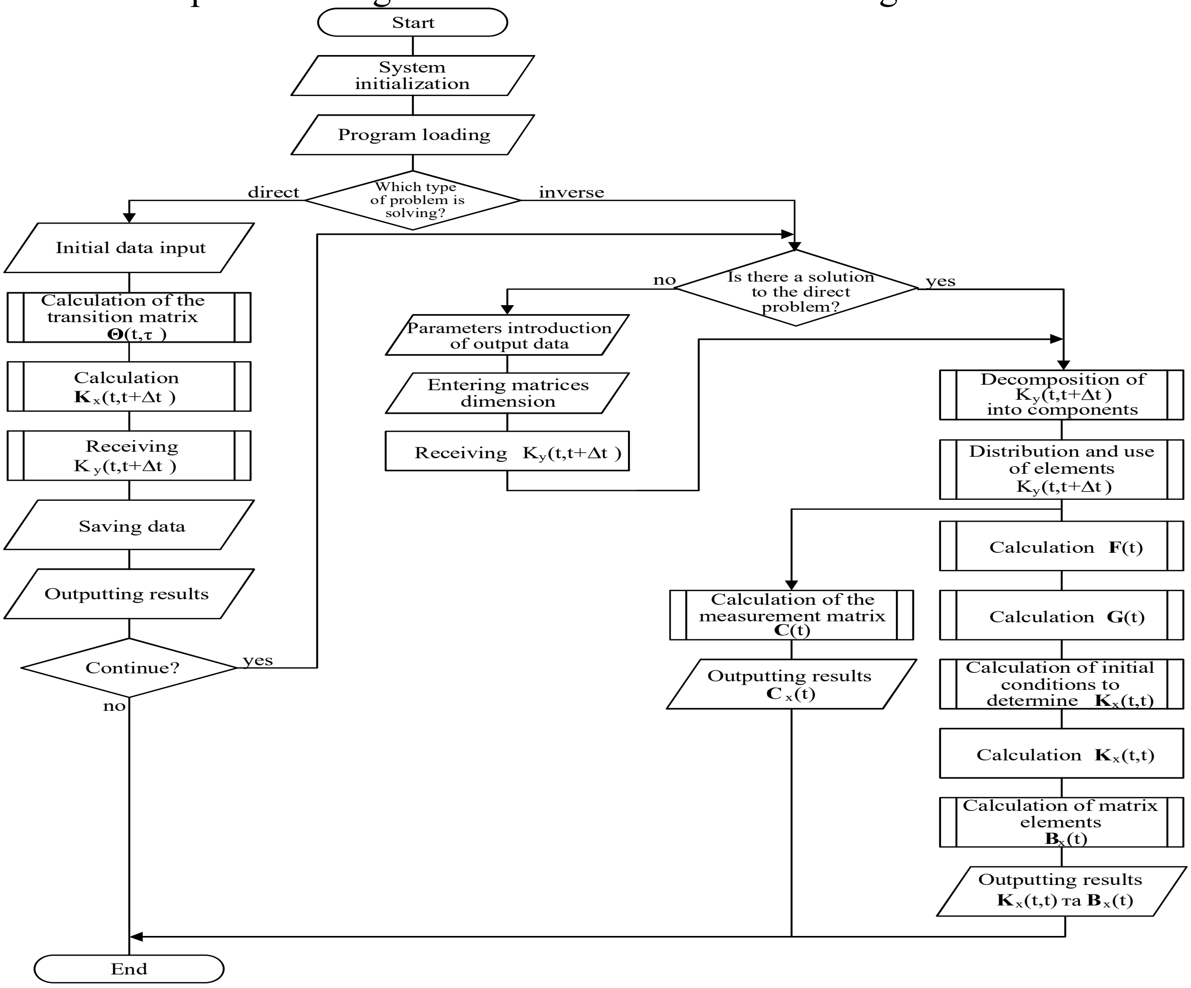


Figure 6 – Stages of the method for identifying and forecasting the state of dynamic systems

The use of the state space method made it possible to reduce the problem of identifying the structure of a dynamic system to solving the Riccati equation. The Riccati equation is reduced by substitution method (10) to a linear differential equation, the solution of which is transformed back into the solution of the Riccati equation, through the solution of which the main matrices of the dynamic system can be determined. Based on one-to-one differentiated transformations of the state vector, the applied procedure allows us to reduce the problem of predicting the state of a dynamic system to the problem of predicting the structure with constant matrices of the state space method.

**3. Development and implementation of an integrated monitoring system and forecasting the state of continuous production.**

The method of modeling the operator of a dynamical system based on the properties of linear operators and ordering experimental data using Hankel quadratic forms and Hankel matrices makes it possible to solve inverse problems of dynamics at the set-theoretic level mathematically in an exact and consistent formulation. This leads to the concept of an optimal accurate model (ignoring noise), namely the strongest irrefutable model in the class of linear systems.

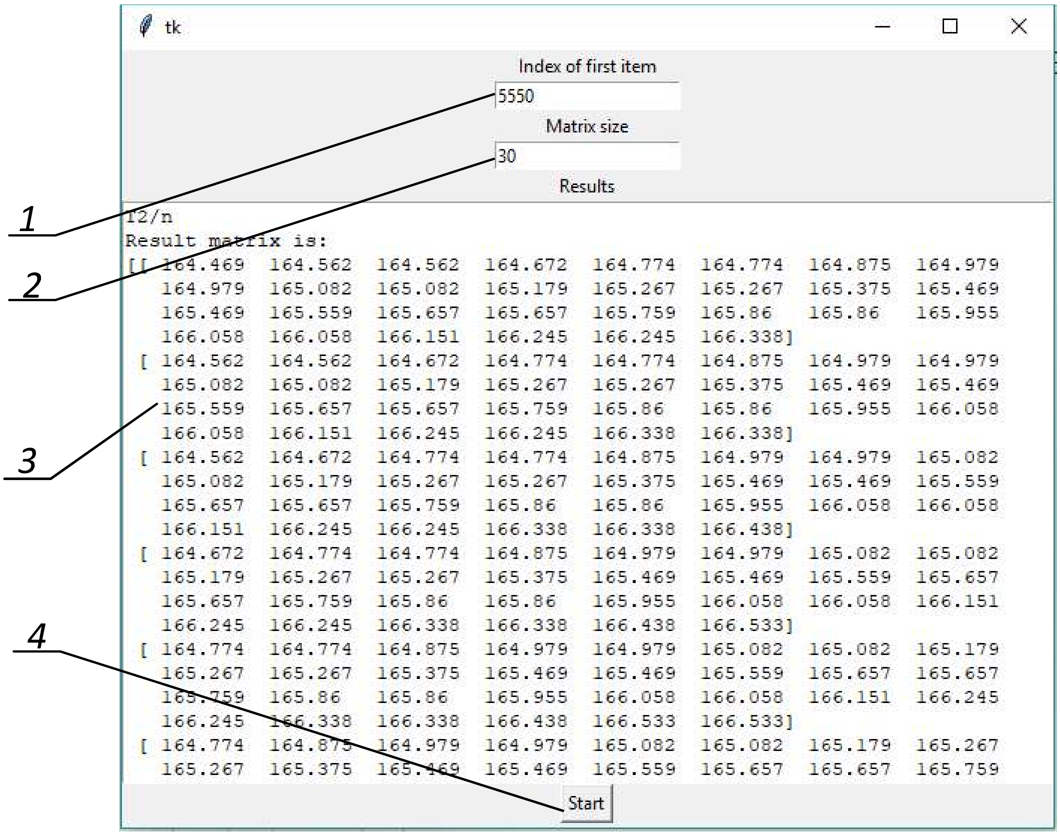
The sequence of constructing a model of an operator of a linear dynamic system as a solution to the inverse problem of dynamics – to determine the structure of the operator in the state space from the output signal – allows us to develop information technologies for real dynamic systems in a linear approximation.

The Python programming language was chosen to develop the program. Development was carried out in the JetBrains PyCharm programming environment, a commercial integrated development environment that allows you to speed up the development process in Python, and the Professional Edition also supports development using Django frameworks and a number of others. To represent matrices, carry out symbolic and numerous calculations, and display graphs, third-party libraries NumPy, SymPy, matplotlib were used *(Димова Г.О., Димов В.С., 2019).*

The input data is the number of the first experimental value, starting from which the Hankel matrix will be built, or the point in time if the «Trinity-factor» software application is connected directly to the technological process, as well as the size of the matrix ($n$–1). To calculate the system parameters, click the Start button. The main program window is shown in Fig. 7.

Based on the fact that the stability of the model of a dynamic system is determined by the structure of matrix **A**, its rank, the type and multiplicity of the roots of the characteristic polynomial and is determined by the location of the eigenvalues on the complex plane, therefore the «Trinity-factor» program calculates the main minors of the constructed Hankel matrix, its eigenvalues. By solving difference equations, the coefficients of the characteristic equation and its roots are calculated. The calculation results window is shown in Fig. 8.

In Figure 9 shows temperature graphs from control devices of the technological installation – drying drum, a continuous technological process for the production of carbon black the Public Joint Stock Company "Kremenchug Carbon Black Plant", namely thermocouples for monitoring flue gases, the drying drum and the temperature of dry carbon black granules for the studied time interval.




1 – number of the first value, starting from which the Hankel matrix is constructed;
2 – matrix size ($n$-1); 3 – data receiving field;
4 – "Start" button, start of calculations

Figure 7 – Main window for finding the system model operator

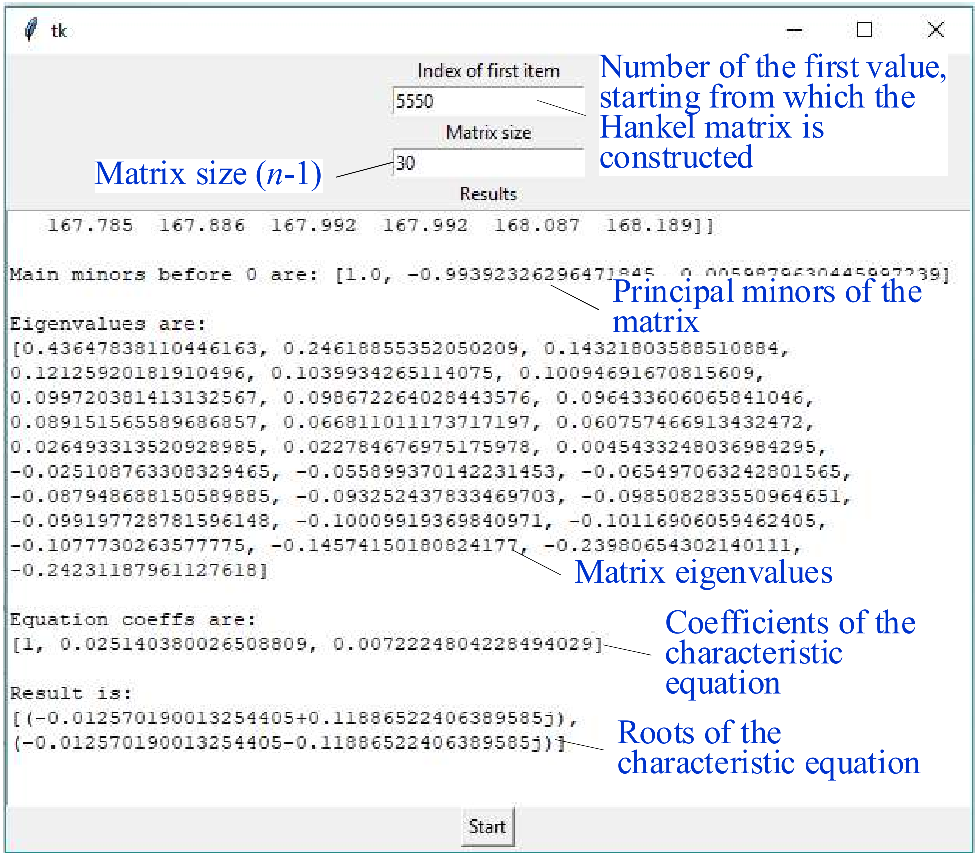



Figure 8 – Results of finding the operator of the system model

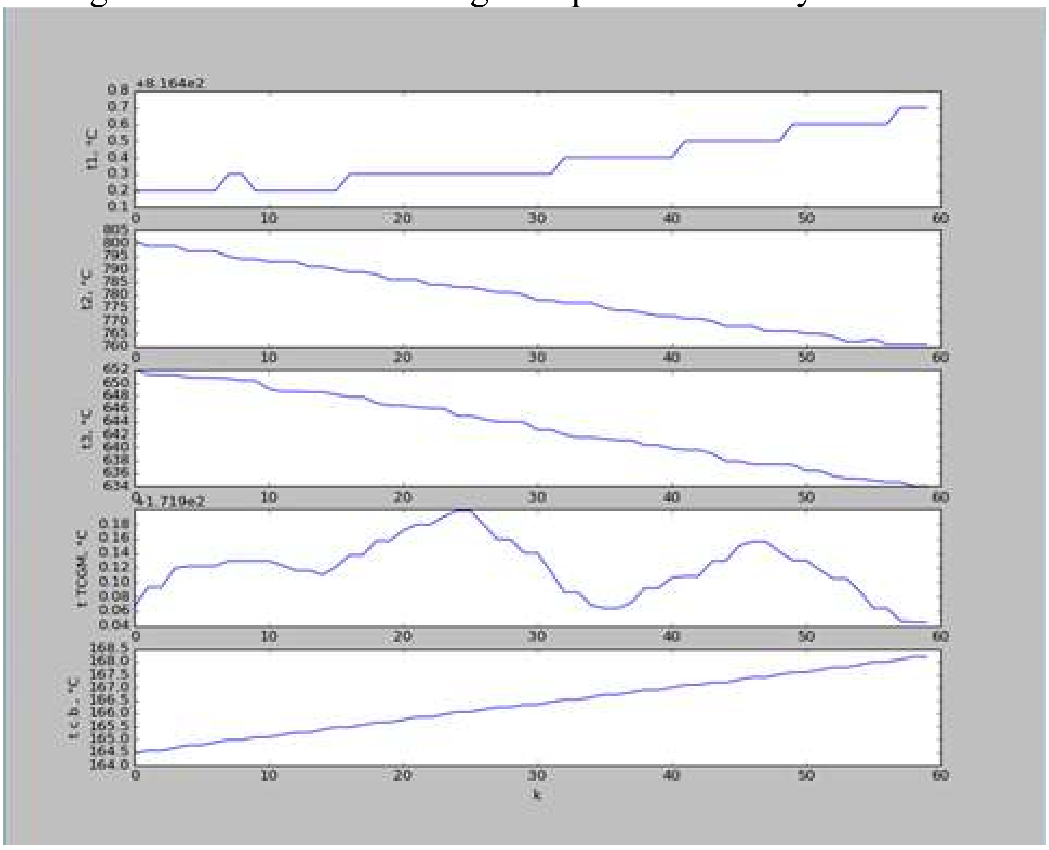



Figure 9 – Temperature graphs from monitoring devices
for the time interval under study

The calculation results are stored in separate MS Excel files.

Based on the results obtained, the initial data for the characteristic equation were calculated and a forecast was made, the error of which was less than 1% (Table 3).

Table 3 – Fragment of the table of results of predicting the state of the system for the time interval under study (temperature of carbon black at the outlet of the installation).

| Time | Output data, °C | | Error, % |
|---|---|---|---|
| | experimental | according to forecast | |
| 11:33:26 | 167,785 | 168,639 | 0,51 |
| 11:33:27 | 167,886 | 168,687 | 0,48 |
| 11:33:28 | 167,992 | 168,734 | 0,44 |
| 11:33:29 | 167,992 | 168,781 | 0,47 |
| 11:33:30 | 168,087 | 168,827 | 0,44 |
| 11:33:31 | 168,189 | 168,874 | 0,41 |
| 11:33:32 | 168,389 | 168,920 | 0,32 |
| 11:33:33 | 168,492 | 168,966 | 0,28 |
| 11:33:34 | 168,492 | 169,011 | 0,31 |
| 11:33:35 | 168,588 | 169,057 | 0,28 |
| 11:33:36 | 168,683 | 169,102 | 0,25 |
| 11:33:37 | 168,683 | 169,147 | 0,28 |

To perform factorization of covariance functions of a dynamic system, you need to move on to the developed method, the stages of which are shown in Fig. 4. The program works as follows: the main script is launched using the command line (using the python model.py command), or using the run.bat file, a task is selected for solution, the initial data for the selected task is entered, the necessary calculations are performed by the program, and the result is output.

The input data of the program are 5 matrices: $\mathbf{A}(t)$ and $\mathbf{B}(t)$ – time-varying matrices of the differential equation; $\mathbf{C}(t)$ – modulation matrix; $\mathbf{Q}$ – covariance matrix of vector white excitation noise; $\mathbf{P}_i(t)$ – cross-correlation matrix between the input of the message source and the additive noise in the channel *(Dymova H., 2021)*.

Writing your own functions to obtain matrices from files adds convenience to writing the main script.

The solution to the direct problem is to compile libraries of behavior models of a dynamic system, that is, libraries of states of transient characteristics of the drying process of carbon black in five different zones of the drying drum. To check the operation of the developed program, matrices were used, calculated by the method of simulating the operator of a dynamic system model, while we do not use the matrix $\mathbf{A}(t)$, with the exception of its dimension.

When executing the program, after solving the direct problem of determining the covariance matrix of the technological process from its description in variable states, results are obtained, which, for ease of demonstration, are depicted as a graph $K_y(t, \tau)$ (Fig. 10).

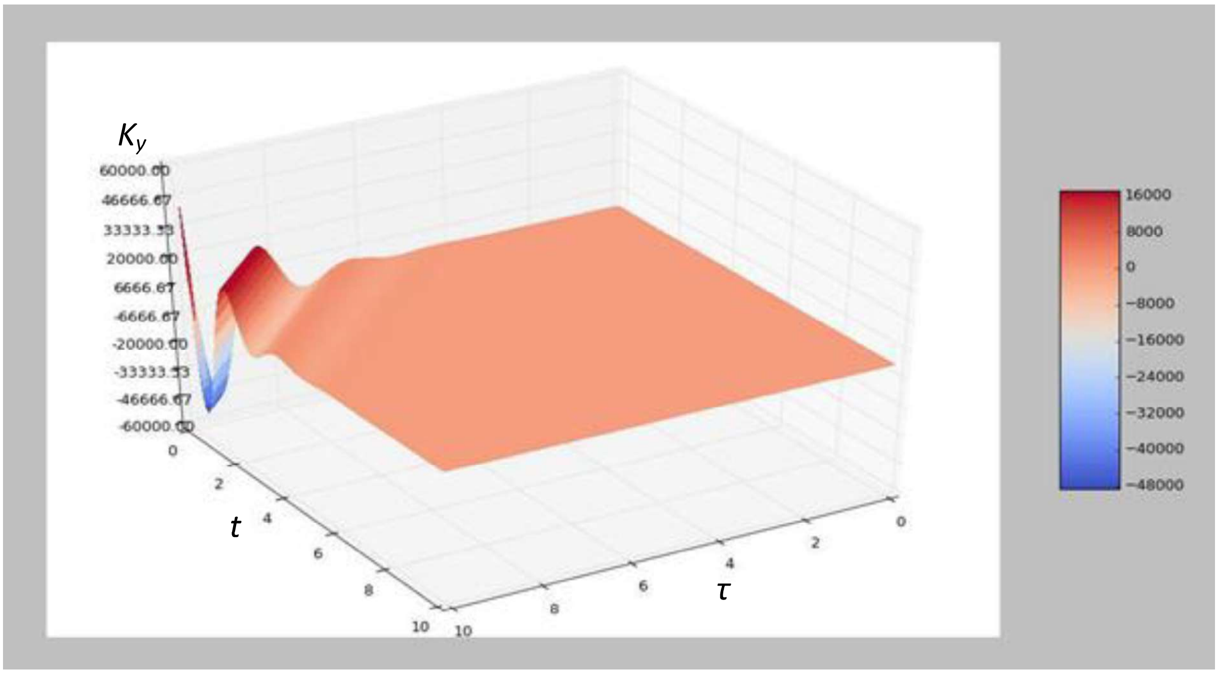



Figure 10 – Graph of the output covariance function $K_y(t,\ \tau)$

To solve the inverse problem, experimental data from the continuous production process are required. The calculation is carried out according to the structural diagram of the implementation of the original process in accordance with the differentiation of its component in the reverse order (Fig. 5). For clarity, the results of calculating the inverse problem of factoring the covariance function are presented in the form of graphs $\mathbf{K}_x(t)$, $\mathbf{C}(t)$ and $\mathbf{G}(t)$ (Fig. 11, 12, 13, 14).

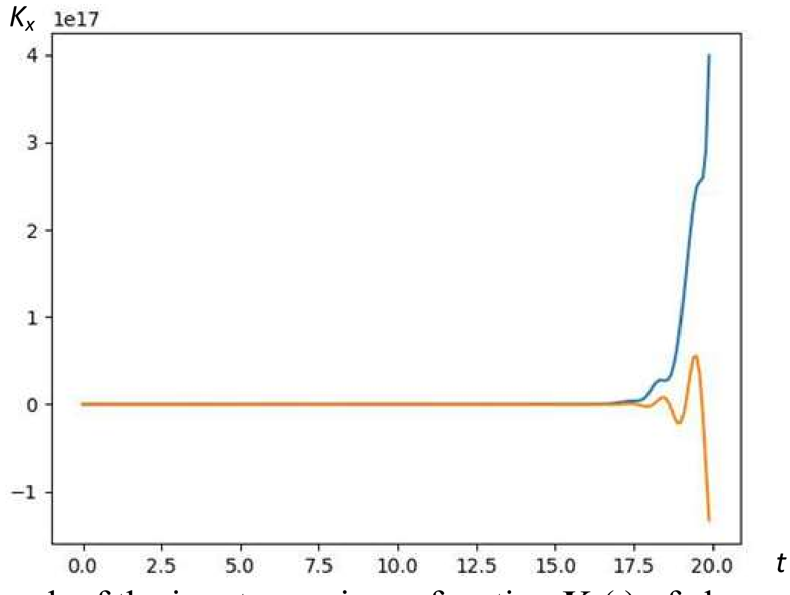



Figure 11 – Graph of the input covariance function $\mathbf{K}_x(t)$ of elements $k_{1,1}$ and $k_{1,2}$

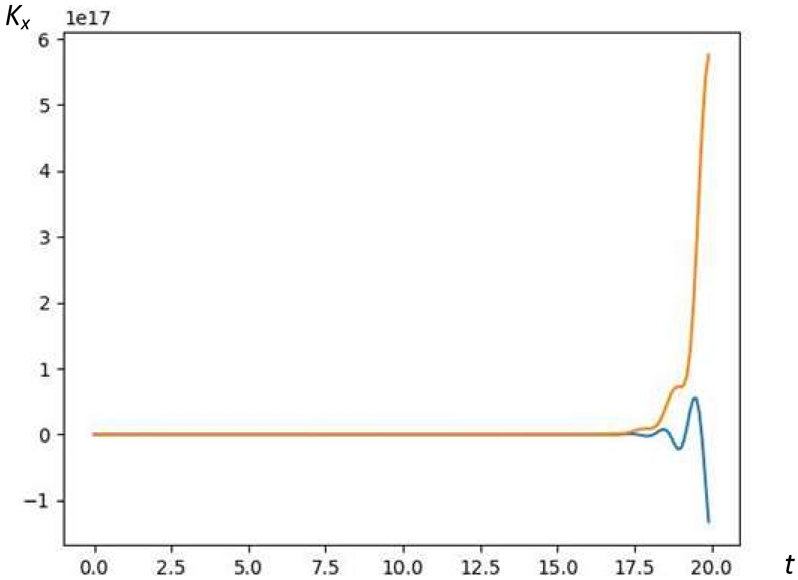



Figure 12 – Graph of the input covariance function $\mathbf{K}_x(t)$ of elements $k_{2,1}$ and $k_{2,2}$

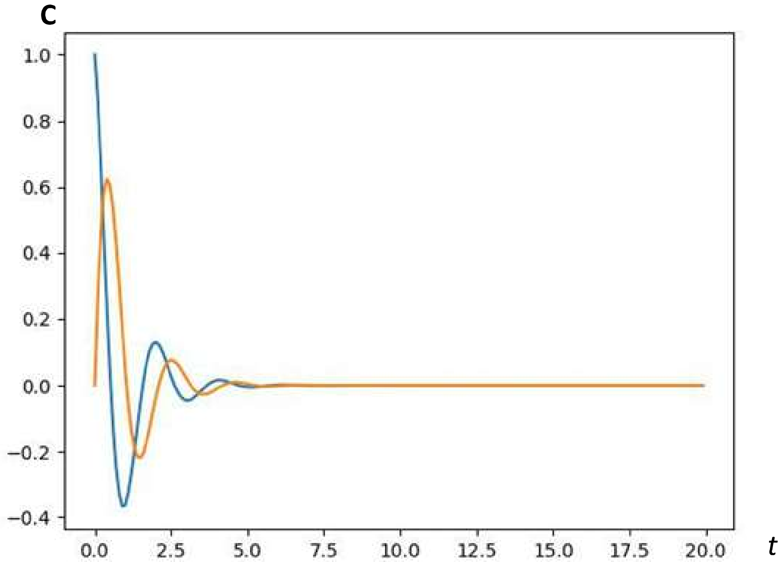



Figure 13 – Graphs of coefficient dependence $\mathbf{C}(t)$

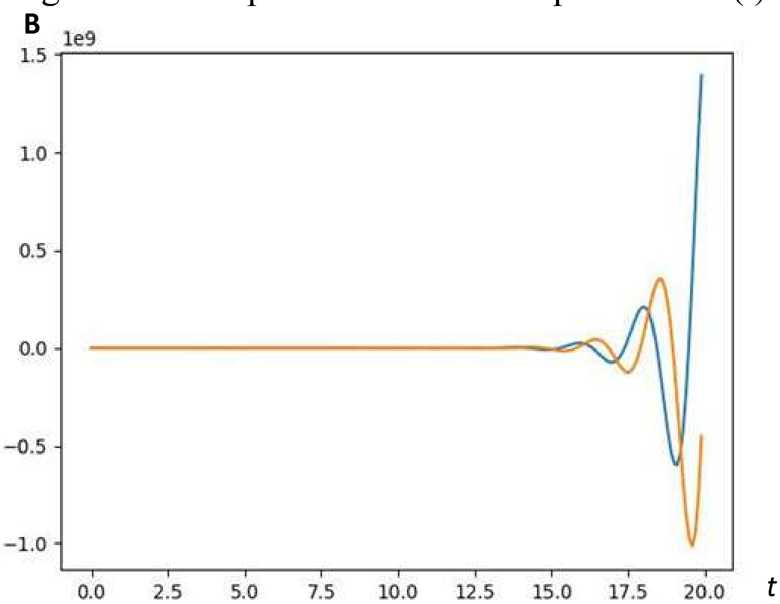



Figure 14 – Graphs of coefficient dependence $\mathbf{B}(t)$

The implementation of the information technology shown in Figure 3 is demonstrated.

**Conclusions and suggestions.** The article demonstrates the development of a system for monitoring technological processes of continuous production to determine the structure of a dynamic object from the output signal, the structure of its operator based on the structural properties of linear operators and compiling a set of output signals of a continuous technological process. Models, methods and information technologies used to identify dynamically undefined systems have been created. Moreover, the use of the state space method made it possible to reduce the problem of identifying the state of a dynamic system to solving the Ricatti equation, which, by improving the method of factorization of covariance functions, allows us to obtain a simpler solution compared to a direct solution. A method for finding a model of a dynamic system has also been developed. It allows you to determine the parameters and characteristics of a dynamic system specified only by the output signal. The difference between the method is that in known problems of identification, management and measurement, information is updated according to two parameters.

A method is proposed for modeling the operator of a dynamical system based on the properties of linear operators and ordering experimental data using Hankel quadratic forms and Hankel matrices, which allows solving inverse problems of dynamics at the set-theoretic level. A method for forming a model of an operator of a linear dynamic system has been developed, which makes it possible to develop computational algorithms for real dynamic systems in a linear approximation.

An information technology has been developed for identifying and predicting the course of a continuous process, allowing for monitoring and predicting behavior throughout the entire drying process. Equations for representing the process based on the measured output parameters are obtained using methods for finding the operator of a dynamic system and factoring covariance functions. Testing of information technology methods for monitoring the technological parameters of the operating mode of a carbon black drying unit was carried out. Currently, a method for finding the operator of a dynamic system model has been introduced into production, where, in contrast to the previously used control at only one point – in the outlet pipe of the carbon-black-gas mixture (CBGM) (zone 13, Fig. 1), control is carried out at five points – three conventional zones of the combustion chamber 10 from thermocouples 4, in the outlet pipe of the CBGM and in the ladle for unloading dry carbon black (zone 11). When the temperature approaches critical, the operator can calculate the stability of the system at each point and predict its behavior for the near future. The forecast error is less than 1%.

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***international collective monograph***

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For scientists, educational staff, PhD candidates, masters of educational institutions, university facilities, stakeholders, managers and employees of management bodies at various hierarchical levels and for everyone, who is interested in current problems of Information Technology, Education, Law, Psychology, Social Sphere, Management through the prism of the possibilities of science and education in the third millennium.

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