Для ефективного керування технологічним комплексом цукрового заводу на основі синтезу синергетичних керуючих стратегій необхідно встановити наявність явищ самоорганізації. Рекурентний аналіз проводився на представленні властивостей складного об'єкта керування у вигляді геометричних просторово-часових структур. Визначені кількісні оцінки детермінованості, стохастичності та хаотичності в поведінці технологічних процесів цукрового виробництва дозволили організувати ресурсоощадні керуючі дії

Ключові слова: рекурентна діаграма, часовий ряд, цукровий завод, синергетичне керування, нелінійна динаміка

Для эффективного управления технологическим комплексом сахарного завода на основе синтеза синергетических управляющих стратегий необходимо установить наличие явлений самоорганизации. Рекуррентный анализ проводился на представлении свойств сложного объекта управления в виде геометрических пространственно-временных структур. Установленные количественные оценки детерминированности, стохастичности и хаотичности в поведении технологических процессов сахарного производства позволили организовать ресурсосберегающие управляющие действия

Ключевые слова: рекуррентная диаграмма, временной ряд, сахарный завод, синергетическое управления, нелинейная динамика

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NON-LINEAR RECURRENT ANALYSIS OF THE BEHAVIOR OF A COMPLEX TECHNOLOGICAL OBJECT

V. Kyshenko
PhD, Professor*
E-mail: vdk.nuft@gmail.com
A. Ladanyuk
Doctor of technical sciences, Professor*
E-mail: ladanyuk@ukr.net
M. Sych
Postgraduate student*
E-mail: a.d.111@bk.ru
O. Shkolna
Postgraduate student*
E-mail: evlens@ukr.net
*Department of automation and intelligent control systems
National University of Food Technologies
Vladimirskaya str., 68, Kyiv, Ukraine, 01601

1. Introduction

Technological complexes (TC) of continuous type, in particular, technological complex of a sugar plant, from the point of view of the tasks of management, are characterized by multidimensionality. It is also worth noting that TC of a sugar factory have all the characteristics of a complex organizational and technological system. Such objects of management are a set of different subsystems that are linked by the processes of intensive interaction and exchange of energy, substance and information. These subsystems are non-linear, multidimensional and deeply-interconnected [1].

Also inherent for this object is the availability of individual stages of the processing of raw materials and semi-finished products, complex connections between the stages. They are implemented on technological equipment of large single power. In this case, the automation of individual stages of TC (departments, subsystems) does not make it possible to achieve high technical and economic indicators of the work of TC in general. They depend on the mutual relations between the subsystems of TC.

The behavior of such objects is characterized by intermittence: alternation of determination, stochasticity and chaotic state [2]. Chaotic processes observed in the behavior of an object and caused by internal factors in many cases play a constructive role in the adaptation of complex objects through self-organization. For efficient control, based on the synthesis of managing strategies that are not forced but topologically agreed, resource saving in nature, of resonance action, it is necessary to conduct the study of such objects of production by the methods of nonlinear dynamics [3].

When creating information managing systems of complex objects, there is always the task of assessing their state. This is caused by a continuous change of both the external environment and the parameters of the object, which is relevant for TC of a sugar factory and requires the use of modern methods of nonlinear dynamics to analyze complex behavior of this managing object. One of the efficient methods of nonlinear dynamics is the recurrent analysis of time series of the variables of the managing object [4]. This method of analysis is based on representing the properties and behavior of the managing object and combines the visual possibilities of their analysis in the form of geometrical space-time diagrams and powerful mathematical apparatus of quantitative ratings – measures to reflect all possible aspects of the behavior of a complex nonlinear managing object that are caused by the intermittency phenomena. Establishing the manifestations of intermittency during the control of technological processes of sugar manufacturing will make it possible to apply adaptive efficient methods of decision making in accordance with the character of the behavior of the object that will lead to saving material and energy resources.

2. Analysis of scientific literature and the problem statement

The paper [5] proposed the method of analysis of nonlinear dynamic systems that expands the possibilities of nonlinear time series analysis, based on the fundamental property of dissipative dynamical systems recurrence (repeatability of states). It is obvious that this method of analysis, based on the representations of properties of the processes in the form of geometric structures, may become a tool for determining dependencies in the observed processes.

The study of complex systems using this method based on the Takens theorem can be carried out in the presence of even one coordinate of the variable of the state, given the fact that by the interaction of variables in complex systems one can judge about the dynamics of the system as a whole.

The papers [6, 7] describe a state of natural or artificial systems that, as a rule, tend to change over time. The study of these complex processes is an important task in many disciplines, enabling to understand and describe their essence. As an example, forecasting the state at some time in the future. The aim of such research is to find mathematical models, which would match the real processes and could be used for the solution of the set problems.

The work [8] is devoted to a fundamental study of the processes, which in nature is characterized by vividly expressed recurrent behavior, such as periodicity or irregular recurrence. Recurrence (repeatability) of states in the sense of following the subsequent trajectory close enough to the previous one is the property of dissipative dynamical systems [9].

If the system reduces its dynamics to a limited subset of the phase space, then the system almost certainly, i.e., with a probability almost equal to one, as much as it can returns to a certain mode, predetermined in advance [10]. The study of complex systems, both natural and artificial, showed that they are based on nonlinear processes, careful study of which is necessary to understand and simulate complex systems.

Over the past ten years a set of traditional (linear) methods of research was significantly expanded with non-linear methods. However, most methods of nonlinear analysis require either long-term or fixed data series, which are quite difficult to obtain. Moreover, the paper [11] revealed that these methods yield satisfactory results for the models of real systems, which are idealized. These factors predetermined the development of new methods of nonlinear data analysis.

Recurrent analysis allows evaluating the characteristics of a nonlinear object at relatively short time series of variables [12] that enables rapid decision making to manage the object. The questions of research into recurrent plots by the time series of technological complex of a sugar plant and their quantitative analysis have not been explored in detail either.

3. The purpose and objectives of the study

The aim of this work is the study of a complex technological complex of a sugar plant by the methods of nonlinear dynamics, which provide necessary possibilities of practical application of the results to forecast further behavior of the object and the development of efficient resource saving strategies of managing a technological complex of a sugar plant.

To achieve the set goal, the following tasks were to be solved:

– analysis of a technological complex of a sugar plant by recurrent plots;

– analysis of graphic representations of a dynamic system;

– quantitative analysis of recurrent plots of time series of technological variables of sugar production.

4. Method of study of recurrent plots by time series of a technological complex of a sugar plant

Based on the Takens theorem, equivalent phase trajectory that preserves the structures of the original phase trajectory can be restored from one time series of the parameter x, put in a pseudo phase space of the set dimension m:

$$x_1^m = (x_1, x_2, \ldots, x_m),$$

$$x_2^m = (x_2, x_3, \ldots, x_{m+1}),$$

$$x_{N-m}^m = (x_{N-m}, x_{nN-m+1}, \ldots, x_N). \quad (1)$$

In [13] they proposed a way to represent m-dimensional phase trajectory of the states of observed process on a two-dimensional quadratic binary matrix of size N×N, where 1 corresponds to the repetition of state at some time and at some other time j while both coordinate axes are the axes of time Fig. 1.

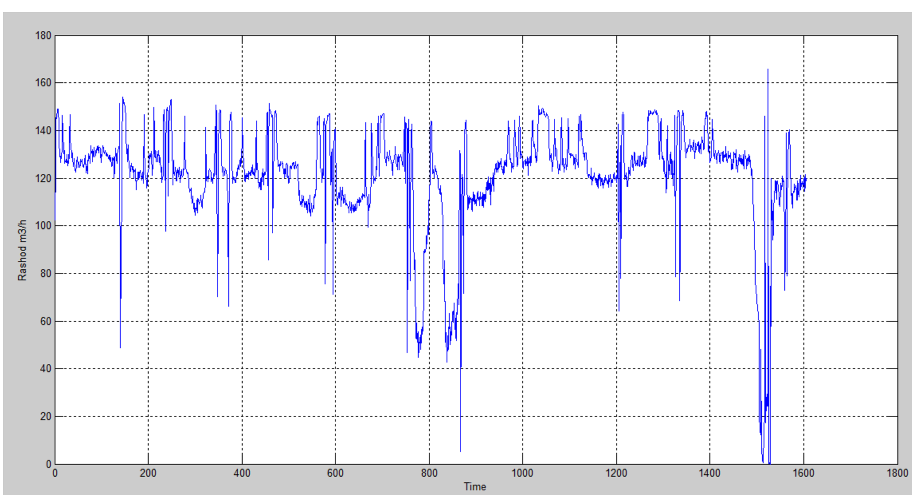

Fig. 1. Time series of change in the consumption of diffusion juice

This graphical representation of the process is called a recurrence plot (RP-recurrence plots) and is the projection of m-dimensional pseudo phase space on the plane [3] (Fig. 2).

Recurrent plot is described by the ratio:

$$R_{i,j}^{m,\varepsilon} = \Theta(\varepsilon_i - \|x_i - x_j\|), \quad (2)$$

where $\{x_i\} = [x_1, x_2, ..., x_N] \in R^m$, $i, j = 1, 2, ..., N$, N are the number of considered states of the observed process, ε_i is the size of the neighborhood of the points x_i in the moment i, $\|x_i - x_j\|$ is the distance between the points, $\Theta(\cdot)$ is the Heaviside function.

For the analysis of the studied processes by recurrent plots, two classes of a structure are used: topology and texture of the images. In this case, topology, which is represented by large-scale structures, provides a general notion about the nature of the process by four classes: homogenous, periodic, drift and white areas. Texture characterizes a small scale structure of the plots and consists of separate points, diagonal, horizontal and vertical lines [14] (Fig. 3–5).

The texture makes it possible to estimate the distance between the states of the system on the diagram of distances [15] that is reflected on some color palette:

$$D_{i,j}^{m} = \|x_i - x_j\|. \quad (3)$$

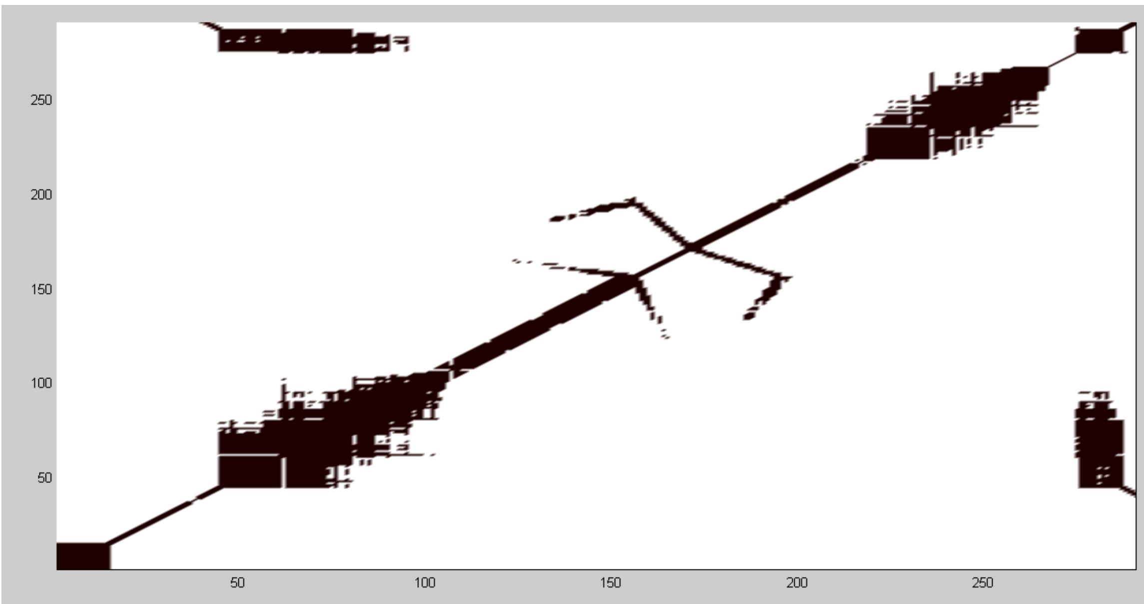

Fig. 2. Representation of the recurrent plot of consumption of diffusion juice (presence of nonstationarity)

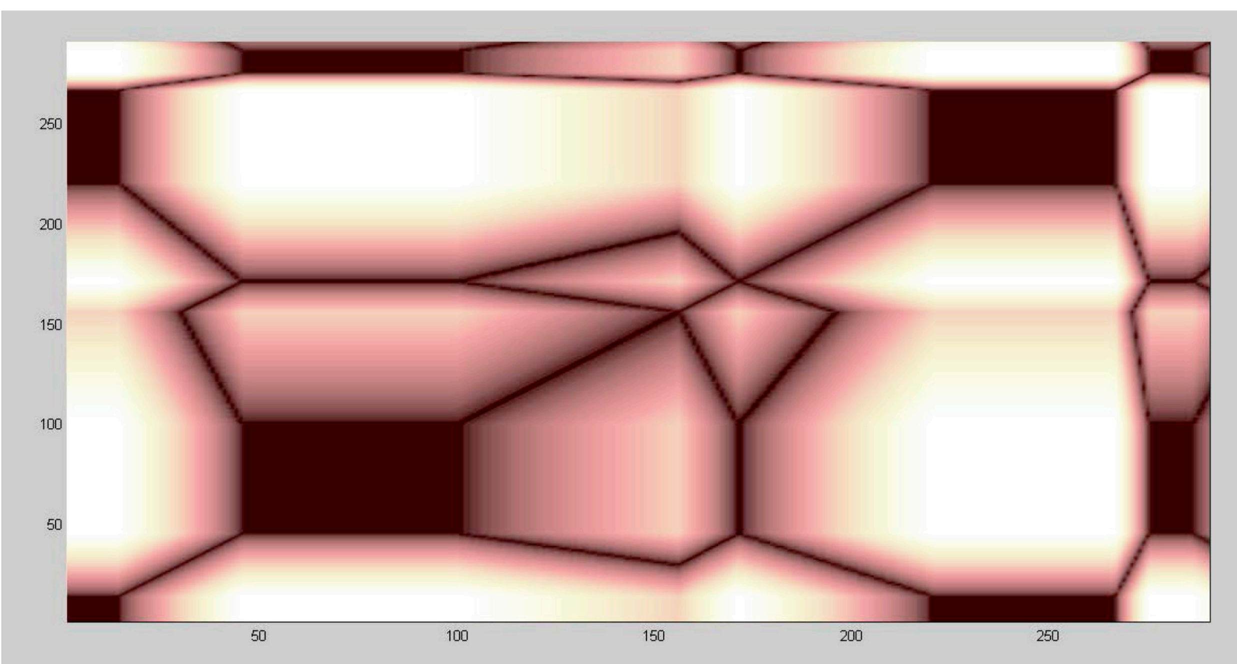

Fig. 3. Representation of the texture of the recurrent plot of consumption of diffusion juice (presence and nature of characteristics drift)

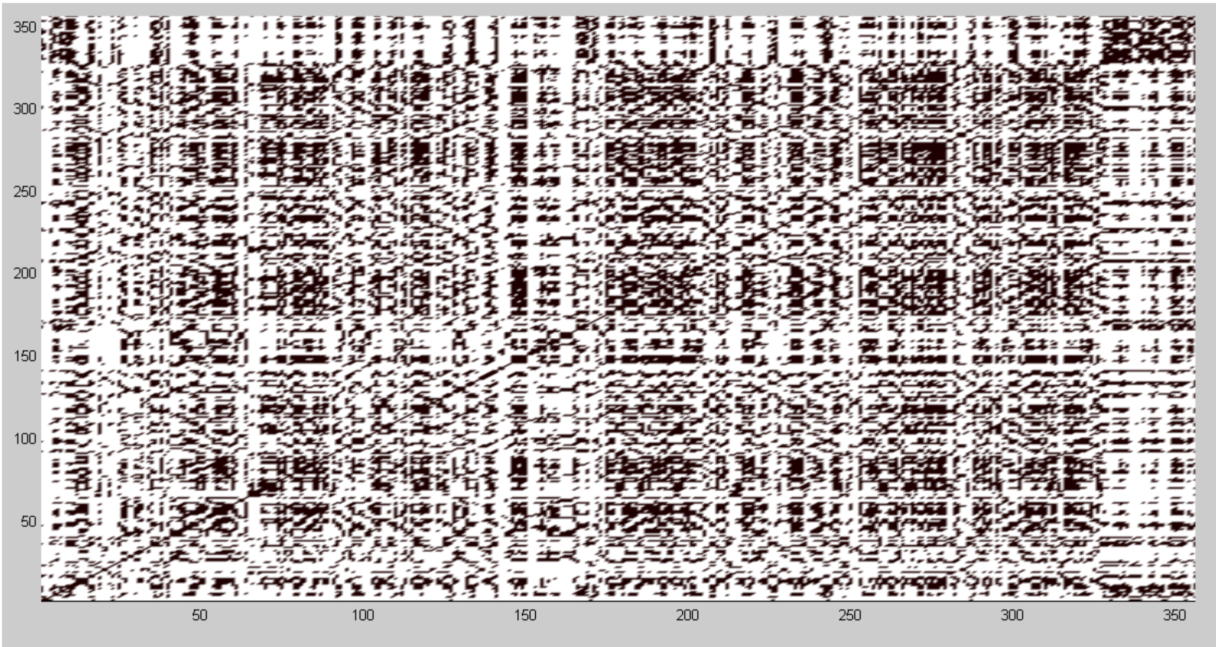

Fig. 4. Representation of the texture of the recurrent plot of consumption of diffusion juice (presence of chaotic process)

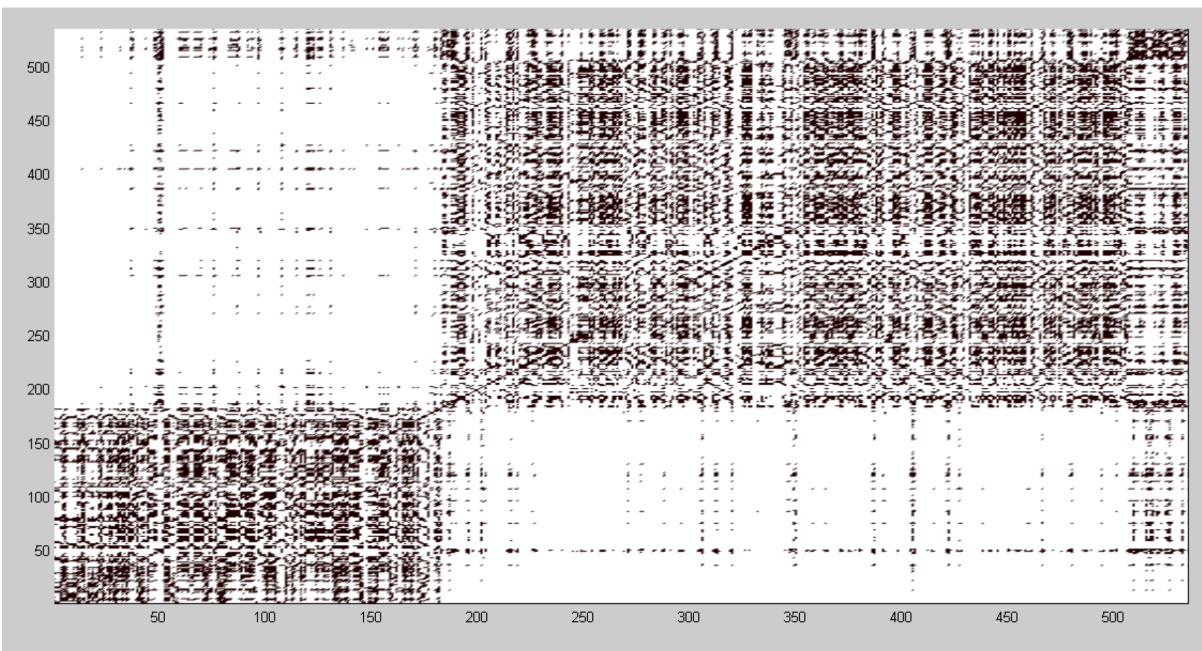

Fig. 5. Representation of the texture of the recurrent plot of consumption of diffusion juice (contrast topology)

After analysis of the graphical representations of the dynamic system, one can determine in which class the system belongs:

– homogeneous, typical for the processes of independent, identically distributed (IID – independent and identical distributed) random values;

– drifting, typical processes with slow (linearly) changing parameters;

– periodic, recurring structures that comply with the oscillating (nonlinear) systems;

– to systems with chaotic behavior.

Based on the obtained recurrent plots, their quantitative analysis was also performed. The method of quantitative analysis of recurrent plots to determine the number of numerical indicators was created by Zbylut and Weber [16]. The essence of the method consists in determining the density of recurrent points and diagonal structures of the plot. As a result of the research into time series of variables during functioning of a technological complex of a sugar plant, we identified the following quantitative indicators as:

– measure of recurrence (RR);

– measure of determination (DET);

– mean length of diagonal lines (L);

– divergence (DIV);

– entropy (ENTR);

– frequency distribution of vertical lines (RATIO);

– trend (TREND).

We also calculated measures that are based on the vertical or horizontal structures of recurrent plots, namely:

– measure of fading (LAM);

– delay indicator (TT).

In most cases, for calculating the measures, the recurrent plots with a constant threshold value were used.

Measure of recurrence was calculated by (4):

$$RR = \frac{1}{N^2}\sum_{i,j=1}^{N} R_{i,j}^{m,\varepsilon}. \quad (4)$$

Measure of recurrence displays the density of recurrent points. It is found by calculating the lines of identity. This measure also indicates a probability of finding a recurrent point in the recurrent plot. Processes with stochastic behavior may form extremely short diagonals or may not form them at all. Processes with deterministic behavior form long diagonals and quite a small number of individual recurrent points.

The ratio of recurrent points that build diagonal structures to the total number of points was defined by (5):

$$DET = \frac{\sum lP^{\varepsilon}(l)}{R_{i,j}^{m,\varepsilon}}, \quad (5)$$

where $P^{\varepsilon}(l) = \{l_l; i = 1...N_l\}$ is the frequency distribution of the lengths l of the diagonal lines in RP; N_1 is the absolute number of diagonal lines (each line is counted only once).

This index is called the degree of determination or predictability of the system.

The minimal length $l_{min} = 1$ is the extreme value, which excludes the presence of diagonal lines that are created by the value of tangent of the motion of trajectory in the phase space. If $l_{min} = 1$, then DET=1. Diagonal structures may determine the time, during which a part of the trajectory passes close enough to another part of the trajectory. One can define the difference of the elements of the trajectory according to these lines.

The next indicator, the mean length of the diagonal line L, shows the time, during which the two parts of the trajectory are close to one another. It may be considered as the average time of predictability and is determined by (6):

$$L = \frac{\sum_{l=l_{min}}^{N} lP^{\varepsilon}(l)}{\sum_{l=l_{min}}^{N} P^{\varepsilon}(l)}. \quad (6)$$

DIV indicator is the divergence, (7) it specifies maximal length of diagonal structures or its inversion:

$$DIV = \frac{1}{L_{max}}, \quad (7)$$

where $l_{max} = \max(l_i; i = 1...N_l)$.

It was found that the lengths of diagonal lines are correlated with the largest positive Lyapunov index in the case when they exist for the studied system. As a result of research, we determined the values of maximal positive Lyapunov index using the width of diagonal lines. The measure of entropy (8) is correlated with the Shannon entropy of the frequency distribution of diagonal lines.

$$ENTR = -\sum_{l=l_{min}}^{N} p(l)\ln p(l), \quad (8)$$

where

$$p(l) = \frac{P^{\varepsilon}(l)}{\sum_{l=l_{min}}^{N} P^{\varepsilon}(l)}$$

shows the complexity of a deterministic component of the system.

The ratio between DET and RR (9) can be calculated from the frequency distribution of diagonal lines [17].

$$RATIO = N_2 \frac{\sum lP^{\varepsilon}(l)}{\left(\sum lP_{\eta}(l)\right)^2}. \quad (9)$$

The studies revealed that this measure may be used for recognition of phase transitions in cases when RR is reduced and DET is unchanged.

$$LAM = \frac{\sum \upsilon P^{\varepsilon}(\upsilon)}{\sum R^{m}, \varepsilon_{i,j}}. \quad (10)$$

The measure of fading LAM (10) displays the ratio of the number of recurrent points that form horizontal lines to the total number of recurrent points. The indicator describes the presence of states of fading of the system. Fading is the state of the system when the motion of this system along the phase trajectory stops or is very slow.

The mean length of horizontal structures (delay indicator) is determined by (11):

$$TT = \frac{\sum_{\upsilon=\upsilon_{min}}^{N} \upsilon P^{\varepsilon}(i)}{\sum_{\upsilon=\upsilon_{min}}^{N} P_{\varepsilon}\upsilon}. \quad (11)$$

This indicator describes the average time, during which the system can maintain more or less stable state. The influence of stochastic component on the system is represented in the plot in the form of occurrence of separately standing points or short diagonal lines. The stochastic component in some cases may not form diagonal lines at all.

5. Results of recurrent analysis of the behavior of a technological complex of a sugar plant

We conducted experimental studies of a technological complex of a sugar plant, which consists of technological subsystems: beet-processing unit, diffusion unit, juice-processing unit, evaporating station, complex of vacuum-devices. During the season of sugar refining in 2015 (September to December), the time series of technological variables) were obtained: beet chips consumption, diffusion juice consumption, syrup consumption; quality of juice, density of the syrup, pH of juice, sugar losses, temperature of juice and others (the total number of variables is 42) (Fig. 1). We performed recurrent analysis of the managing object's behavior in various situations at changing technological modes, quality of raw beets, at a different turbulence of material flows. The time series of various durations (from 20 minutes to 4 hours) were analyzed during the season of sugar refining. We obtained topologies and textures of recurrent plots, which are given on the example of consumption of diffusion juice in Fig. 2–5. Recurrent analysis allowed us to identify the nature of the processes (stochasticity, randomness, frequency, quasi–periodicity, etc.), to determine the features of the evolution in the behavior of the managed object (change in the mode, change in the level of noise, change in trends, etc.), to conduct a comparison of the processes (identification of similarity, deviations from the standard, synchronization, etc.), to assess the nature of nonstationarity, to characterize the degree of laminarity and turbulence of material flows for their consideration in the process of decision making about management.

For a representative analysis of recurrent plots, along with the identification of topology and texture, we assessed quantitative characteristics of the features of behavior (Table 1) by the following indicators: measures of recurrence, determination, and the average time of predictability, divergence, fading, entropy and others. Given the differences in the estimates of these parameters in different periods of functioning of the managed object that validates the multifarious nature of its behavior, we performed adaptation of the parameters of the algorithms in management in line with situational environment.

Table 1

Quantitative analysis of the recurrent plots of consumption of diffusion juice

Indicator	Time series 1	Time series 2	Time series 3
RR	0,198	0,098	0,126
DET	0,657	0,474	0,513
L	2,861	3,552	2,845
DIV	0,029	0,024	0,037
ENTR	1,359	1,471	1,261
RATIO	4,675	5,394	4,537
LAM	0,463	0,631	0,581
TT	4,131	2,732	3,783

6. Discussion of the results of recurrent analysis

The practical value of the obtained recurrent plots describing various aspects of the behavior of a technological complex of the sugar factory as the object of management is in the accumulation of a large amount of information through its visualization and allowing assessment of characteristic features of the behavior of technological processes. It also allows forecasting and adopting efficient solutions to eliminate possible negative consequences.

The topology of recurrent plots (Fig. 2) indicates the presence of drift characteristics that is characterized by the presence of black zones that correspond to the accumulation of vertical and horizontal lines in the area, remote from the main diagonal. The features and magnitude of the drift characteristics of the object are determined by the texture of the recurrent plot (Fig. 3) when changing brightness of the images.

The intermittence was defined in the behavior of the managed object through formation of chaotic space-time patterns (Fig. 4), which is characterized by irregular manifestations of diagonal lines [3, 6]. The contrast topology of the time series (Fig. 5) describes sharp change in the dynamics of technological processes, substantial nonstationarity, due to which the outlined white zones appear in the structure of the recurrent plot.

Abrupt changes in quantitative evaluations of the indicators of recurrent plots indicate presence of the intermittency phenomena in the behavior of the object, significant dynamic changes in its characteristics, which requires the use of adaptive algorithms of management.

7. Conclusions

1. We analyzed a technological complex of a sugar plant with the help of nonlinear recurrent analysis using two classes of structures: topology and texture of the images. It was determined that this object obeys laws of the theory of dynamic chaos and displays intermittency phenomena.

2. A visual exploration of graphic representations of the main indicators of a TC of sugar factory was conducted. As a result it was established that the object is characterized by the presence of noises, drifts in the characteristics and change in the nature of behavior.

3. We conducted quantitative analysis of recurrent plots of time series of technological variables in sugar production to determine the density of recurrent points and diagonal structures. The features of manifestations of behavior of technological processes of sugar refining were identified, in particular, the presence of chaotic modes. This, in turn, enables to develop efficient systems of synergetic management that ensure maximal utilization of own resources of the managed object by the phenomena of self-organization.

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