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RECURRENT ANALYSIS OF ENERGY CONSUMPTION OF A METALLURGICAL ENTERPRISE

The subject of the study is the study of models and methods for short-term forecasting of energy consumption in power systems based on recurrent analysis of time series. **The aim of the work** is a recurrent analysis of the time series of energy consumption of a metallurgical enterprise and the development of a program in the *Matlab* environment for automating calculations and experimental testing of data available for research in PJSC Electrometallurgical Plant "Dniprospetsstal" named after A. M. Kuzmin. The following **tasks** have been solved: the methodology for constructing recurrent diagrams and their quantitative analysis have been considered; a model of the time series and the phase trajectory of the time series was built to visualize the change in energy consumption during the day; software for constructing recurrent diagrams in the *Matlab* package was developed. **Methods were used**: analysis of time series based on recursive analysis to study the characteristics of the state of the system on the example of a metallurgical enterprise. **The results were obtained**: software was developed in the *Matlab* environment for short-term forecasting of energy consumption in power systems, and quantitative indicators were calculated that can be used to characterize the state of the system and analyze energy consumption in the summer and winter seasons. **Conclusions:** in the course of the study, software for constructing and quantitative analysis of recurrence diagrams in the *Matlab* package was developed, with the help of which patterns were discovered and information about the properties of the system under study was obtained. Based on the analysis of the average values of quantitative measures in the off-season for 2018–2021, it can be seen that the summer period is characterized by greater predictability, as well as a significantly higher latency indicator, which characterizes the average time when the system can spend in a more or less unchanged state. Confirmed on real data, the benefits of using the recursive analysis method for estimating electricity consumption, as well as more efficient modeling of this process, can lead to an increase in the accuracy of forecasting its future dynamics.

Keywords: recurrent diagram; energy consumption; time series; non-linear dynamics.

Introduction

Ferrous metallurgy is one of the most energy-intensive industries. It is characterized by high electricity consumption, which is a significant component of energy costs. Thus, the share of electricity in the production cost of large enterprises in the industry ranges from 11% to 16%, and in some cases its share increases to 30% [1].

The process of energy consumption in the metallurgical industry belongs to a complex dynamic system characterized by irregular behavior dynamics, which is manifested by both random and deterministic chaotic processes [2]. Observations of such systems and their experimental studies should be represented by time series – a discrete sequence of random variables, which are the values of the relevant indicators ordered by the time of their receipt. Time series also determine the state of the object of observation at certain points in time. The main purpose of time series analysis is to obtain information about the properties and mechanism of the system that generates this series. They are the basis for modeling such systems.

Planning the operating modes of the energy system is the most important task in managing it, and the efficiency and economic profitability of a steel company depends on solving this task. For this purpose, a forecast of electricity consumption is developed, which is a basic indicator. The planning of the electricity distribution balance, as well as the modes of electricity supply, is based on the forecasted value of energy consumption. Thus, the accuracy and reliability of the forecast directly affects the technological and economic aspects of the power system. The data obtained from the system under study often demonstrate its non-stationary and complex behavior. In addition, such systems are often observed with very few measurements, providing short data series. Linear time-series analysis approaches are often insufficient for studying this kind of data, and most nonlinear analysis methods require either rather long or stationary data series. A relatively new method of studying the complexity of system dynamics is the construction of recurrent diagrams.

Recurrent analysis in the study of dynamic systems does not require a large amount of primary data, a time series of data from one measurement experiment is sufficient. Recurrent diagrams obtained in the process of time series analysis are based on a geometric structure. The main diagonal on a recurrent chart looks like a black diagonal line – the identity line. The individual points on the chart do not contain any information, but together they allow you to reconstruct the properties of the process under study.

Recurrent analysis is based on the repeatability property of dynamic systems, which can be used to characterize the behavior of such a system in phase space. The advantage of this method is that it allows you to study the multidimensional trajectory of the phase space using a two-dimensional representation of its recurrence [3]. Using recurrent diagrams to analyze time series allows not only visualizing but also quantifying the structures hidden in the data.

Analysis of recent research and publications

Since the main method used for this study is recurrent analysis, we will provide a brief overview of the results on the development of this method. In an article published in 1987, Eckman, Kamphorst, and Ruel [4] proposed a new graphical procedure for visualizing patterns of repetition in data, which they called a recurrence chart. Thus, the way was paved for the introduction of a modern tool for nonlinear data analysis, which made it possible to overcome the difficulties in studying non-stationary and rather short time series.

Among the advantages of the developed method are simplicity of implementation and interpretation, as well as fewer preliminary data requirements. However, recurrent charts were only a visual and qualitative tool, meaning that the user had to search for and interpret the identified patterns and structures on his or her own, which meant that the results were not always convincing. Therefore, the next stage in the development of recurrent analysis was the method of quantitative analysis of structures formed in the image of a recurrent diagram. Modern research has shown that a recurrent diagram contains all the necessary information about the dynamics of a system. The works of such scientists as Joe Zbilut [5], Norbert Marwan [6], Marco Thiel [7], Carmen Romano [8], and others have significantly enriched the capabilities of this method over the past decade.

Examples of the practical application of the recurrent analysis method in the financial sector are given in [9], where the optimal values of input parameters and appropriate measures for analyzing financial time series are determined in order to build a market-monitoring tool.

Paper [10] analyzes the possibility of using recurrent analysis to detect signals and process observations. It is shown that the presence of noise in observations worsens the quality of signal detection using the numerical characteristics of recurrent charts.

A method for quantifying the phase trajectory of the process under study using recurrent diagrams and their quantitative analysis was proposed in [11] and the results of applying this method to model and real systems are presented. For this purpose, an assessment of the possibilities of using this method is presented.

The use of recurrent analysis for modeling and predicting the nonlinear dynamic properties of complex systems is considered in [12]. The concepts of phase space reconstruction, recurrent analysis, recurrent diagrams, and their characteristics, such as topology homogeneity, drift, contrast topology, and process laminarity, are presented.

In [13], a comparative recurrence and entropy analysis of realizations of electrical bio signals with fractal properties was performed. It is shown that the information characteristics of the experimental results reflect the features of the fractal and correlation structure of bio signals. With the help of the developed decision support system, model and experimental implementations have been investigated, which have shown the feasibility of using information characteristics for the recognition and classification of fractal time series.

Among the considerable number of publications on the use of the recurrent analysis method, there is not a single example of the application of this method to the analysis of energy consumption in metallurgy. Therefore, this article is devoted to this area of research.

Statement of the problem

In the study of energy consumption in metallurgical production, there is a need to analyze short time series, which is associated with:

– a significant number of electrical equipment used in the technological process in each unit;

– a wide variety of types and capacities of electricity receivers;

– relatively weak links of mutual influence of electricity receivers during the technological process;

– a significant amount of electrical equipment that ensures the technological process in each unit and creates a conditionally constant load, which also depends on the intensity of the technological process;

– factors that accidentally affect the mode and volume of energy consumption;

– a large number of hours of maximum electrical power utilization;

– significant power consumption of the types of final products;

– the possibility of changing the operating modes and composition of equipment in the units, product mix and other systematic factors [2].

Therefore, the purpose of this article is to recurrently analyze short time series of energy consumption of a metallurgical enterprise and develop a program in *Matlab* to automate calculations.

To achieve this goal, the following tasks need to be accomplished

– to study the theoretical foundations of the method of building recurrent diagrams and their quantitative analysis;

– develop software for building and analyzing recurrent diagrams;

– to apply the method to real data describing a complex dynamic system of hourly electricity consumption at a metallurgical enterprise;

– to identify patterns and obtain information about the properties of the system under study;

– to draw conclusions from theoretical and practical results of the study;

– to evaluate the effectiveness of the method under consideration.

Materials and methods

The essence of recurrent diagrams is to visualize the functional activity and dynamics of systems based on the results of observation, which allows you to understand the basic properties and structures. Dynamic systems, i.e. systems in which parameters change over time, are described by observing changes in their states and indicating the functional dependence of the system's state on the values at its inputs at specific moments in time. In the mathematical sense, any dynamic system can be represented as the movement of a corresponding point in a phase space, or state space. The main characteristic of such a space is its dimension. The number of quantities that determine the state of the system determines the dimension of the phase space. Each of these quantities is a phase coordinate in this space, and their combination forms a vector that describes the state of the system. Each state of the system corresponds to a certain point in the phase space - a representation point. The sequence of these points in the phase space reflects the movement of the system or, more precisely, the change of system states, and corresponds to a certain trajectory, which is called a phase trajectory. The projection of the phase trajectory onto the phase plane forms a phase portrait. The graphical representation of the phase trajectory characterizes the behavior of the system. In the study of complex systems, they can often be characterized even by a single observable indicator measured at discrete points in time D_t, since it is either impossible or very difficult to measure other indicators. The interval D_t can be a constant value or random, although in the latter case it creates additional and sometimes significant difficulties in processing the observed data. The interactions in complex systems are such that the resulting phase trajectory, which preserves the structure of the original phase trajectory, can be recovered, according to Tuckens' theorem [13], from a single time series by the time-delay method. That is, if we have a time series $X(t)= x(t_1+\Delta t), x(t_2+\Delta t),\ x(t_n+\Delta t)$, then, using the time delay method, for example, in our case $\Delta t=1$, we obtain the series $\Delta t=1$ $X(t)= x(t_1+\Delta t), x(t_2+\Delta t)\ldots x(t_n+\Delta t)$. The pairs of values $\left(x(t_i); x(t_i+\Delta t)\right)$ are the phase coordinates of the image point on the phase plane, which reproduces the phase trajectory of the system states. Graphically, the dynamics of the system in a limited area of the phase plane is represented by the image of phase trajectories. Over time, the system tends to return to a certain state, to some extent close to the past, and goes through similar states of evolution.

Let us consider in more detail the method of recurrent analysis, referring to the work of N. Marwan et al. [14].

Nonlinear data analysis is based on the study of phase space trajectories. Elements of the phase space are possible states of the system under study. Let's assume that the state of such a system at a fixed time t can be specified by d components. These parameters form a vector in the d-dimensional phase space of the system:

$$\vec{x}(t)=\left(x_1(t), x_2(t), .., x_d(t)\right)^T. \qquad (1)$$

Thus, a vector $\vec{x}(t)$ defines a trajectory in phase space.

The recurrent diagram maps the trajectory $\vec{x}_i \in R^d$ in d-dimensional phase space to a two-dimensional square binary matrix of size N×M:

$$R_{i,j}(\varepsilon)=\Theta\left(\varepsilon_i-\left\|\vec{x_i}-\vec{x_j}\right\|\right), i, j=1,\ldots,N, \qquad (2)$$

where N – number of states $\vec{x}_i$;

ε – threshold distance;

$\theta(\cdot)$ – Heaviside function $\left(\theta(x)=0\right.$, if $x<0$, & $\theta(x)=1$ otherwise);

$\|\cdot\|$ – norm.

The shape of the circle, characterized by the parameter ε_i, is determined by the type of selected norm and is centered on the point $\vec{x}_i$, that is, the radius of the circle in phase space centered at the point $\vec{x}_i$. In the case of a one-dimensional time series, instead of a figure's circle, there is an interval with the center at the point $\vec{x}_i$. If a point $\vec{x}_j$ is in the middle of this circle, then this state $\vec{x}_j$ is considered similar to the state $\vec{x}_i$, and a point $R_{i,j}=1$ is placed on the diagram. Radius ε_i can be permanent for all $\vec{x}_i$, and can be determined for each point separately, so that the resulting circle always includes a certain number of similar states. The constant value of ε_i, which leads to a symmetric recurrent diagram with respect to the line $R_{i,j}=1$, if $(i=j)$ is the main diagonal of the distance matrix.

In other words, recurrence $\vec{x}_i$ and $\vec{x}_j$ is defined as the closeness of a state $\vec{x}_i$ to the state $\vec{x}_i$. In the process of constructing recurrence diagrams, the norm L_∞ is mainly used due to its simplicity and speed of calculation.

The recurrence diagram is obtained by constructing the recurrence matrix (2) and using different colors for its binary values (usually black for $R_{i,j}=1$ and white for $R_{i,j}=0$), and both coordinate axes are time axes. Since, by definition, $R_{i,j}=1$ under the condition $i=j$, the recurrent diagram always contains a black main diagonal line – the identity line. In addition, the definition implies that the recurrence diagram is symmetric about the main diagonal, since $R_{i,j}=R_{j,i}$ for any $i,j=\overline{1,N}$.

The main purpose of recurrent diagrams is to visually analyze trajectories in multidimensional phase spaces, which gives an idea of the evolution of these trajectories over time. A recurrent diagram is characterized by large-scale and small-scale structures that are caused by the dynamic state of the system.

Large-scale structures give a general idea of the nature of the process under study. As a rule, the following large-scale structures of recurrent charts are distinguished:

a) homogeneous, which is typical for stationary and autonomous systems;

b) periodic, which corresponds to oscillating systems;

c) drift corresponds to systems with slowly changing parameters;

d) contrasting areas or bands correspond to systems with sharp changes in dynamics.

Small-scale structures include:

a) diagonal lines reflecting similar local evolution of different parts of the trajectory;

b) horizontal and vertical lines indicate a state that does not change for some time or changes very little;

c) separately located recurrent points, but they do not contain information about the state of the system.

Quantitative analysis allows to calculate measures of the complexity of recurrent diagram structures based on the density of recurrent points, diagonal, vertical and horizontal lines.

The recurrence rate reflects the density of recurrent points:

$$RR=\frac{1}{N^2}\sum_{i,j=1}^{N}RR_{i,j}\,. \tag{3}$$

The following measure is based on diagonal lines of length l, namely:

$$P(l)=\sum_{i,j=1}^{N}\left(1-R_{i-1,j-1}\right)\left(1-R_{i+1,j+1}\right)\prod_{k=0}^{l-1}R_{i+k,j+k}\,. \tag{4}$$

The ratio of the number of recurrent points that are components of diagonal lines (of minimum length $l_{\min}$) to the total number of recurrent points is called the rate of determinism, or predictability of the system:

$$DET=\sum_{l=l_{\min}}^{N}lP(l)\Big/\sum_{l=1}^{N}lP(l)\,. \tag{5}$$

Processes with stochastic or chaotic behavior generate very short diagonals or no diagonals at all, while deterministic processes produce long diagonals and a small number of separate, isolated recurrent points. That is, as the stochastic influence decreases, the value of the determinism measure will increase.

The length of the diagonal line reflects the period during which different segments of the trajectory pass close enough to each other at different times. Therefore, such lines are associated with the divergence of trajectory segments.

The average length of the diagonal lines reflects the average time during which two trajectory segments pass close to each other and can be considered as the average time of predictability:

$$L=\sum_{l=l_{\min}}^{N}lP(l)\Big/\sum_{l=l_{\min}}^{N}P(l)\,. \tag{6}$$

Maximum length of diagonal lines and divergence:

$$L_{\max} = \max\{l_i\}_{i=1}^{N_l}, DIV = \frac{1}{L_{\max}}, \qquad (7)$$

where N_l – total number of diagonal lines.

The faster the trajectory segments diverge, the shorter are the diagonal lines and the higher is the rate DIV. The inverse of the maximum length of the diagonal lines can also be interpreted as the value directly related to the maximum positive Lyapunov exponent, if it exists for this system [15].

The entropy rate is found by the Shannon entropy, to calculate which probability $p(l) = \frac{P(l)}{N_l}$ we find a diagonal line of length l:

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

This rate reflects the complexity of the recurrence diagram with respect to the diagonal lines. That is, for example, for uncorrelated noise, the ENTR value is quite small, which indicates its insignificant complexity.

The next rate was defined as the ratio between *DET* and *RR*, namely:

$$RATIO = N^2 \frac{\sum_{l=l_{\min}}^{N} lP(l)}{\left(\sum_{l=l_{\min}}^{N} lP(l)\right)^2}. \qquad (9)$$

This relation can be used to recognize phase transitions in cases where the *RR* rate decreases and the *DET* rate remains constant.

Next, consider a rate based on vertical lines of length υ, namely:

$$P(\nu) = \sum_{i,j=1}^{N} \left(1 - R_{i,j}\right)\left(1 - R_{i,j+\nu}\right)\prod_{k=0}^{\nu-1} R_{i,j+k}. \qquad (10)$$

The laminarity rate is determined by the ratio of the number of recurrent points that form vertical lines (of minimum length $\nu_{\min}$), to the total number of recurrent points:

$$LAM = \frac{\sum_{\nu=\nu_{\min}}^{N} \nu P(\nu)}{\sum_{l=l_{\min}}^{N} \nu P(\nu)}. \qquad (11)$$

This value characterizes the presence of system stalling states, i.e. when the system's movement along the phase trajectory stops or moves very slowly.

The average length of the vertical lines, that is called the trapping time rate, reflects the average time during which the system will be in a certain state, or how long this state will remain unchanged:

$$TT = \sum_{\nu=\nu_{\min}}^{N} \nu P(\nu) \Big/ \sum_{l=l_{\min}}^{N} \nu P(\nu). \qquad (12)$$

Let us further consider the application of quantitative characteristics to the analysis of short time series of energy consumption of a metallurgical enterprise.

Research results and their discussion

The study was conducted on the basis of observations of the complex dynamic system of hourly electricity consumption at PrJSC "Dneprospetsstal" [2] during 2018–2021.

To illustrate the results of constructing recurrent diagrams, let us consider, for example, the time series of hourly energy consumption for February 04 and July 04, 2021. The recurrence of the trajectory in phase space is expressed by matrix (2). Therefore, for the studied series, we set $N = 23$, $\varepsilon = 10000$. The recurrent daily diagrams obtained in *Matlab* are shown in figs. 1 and 2.

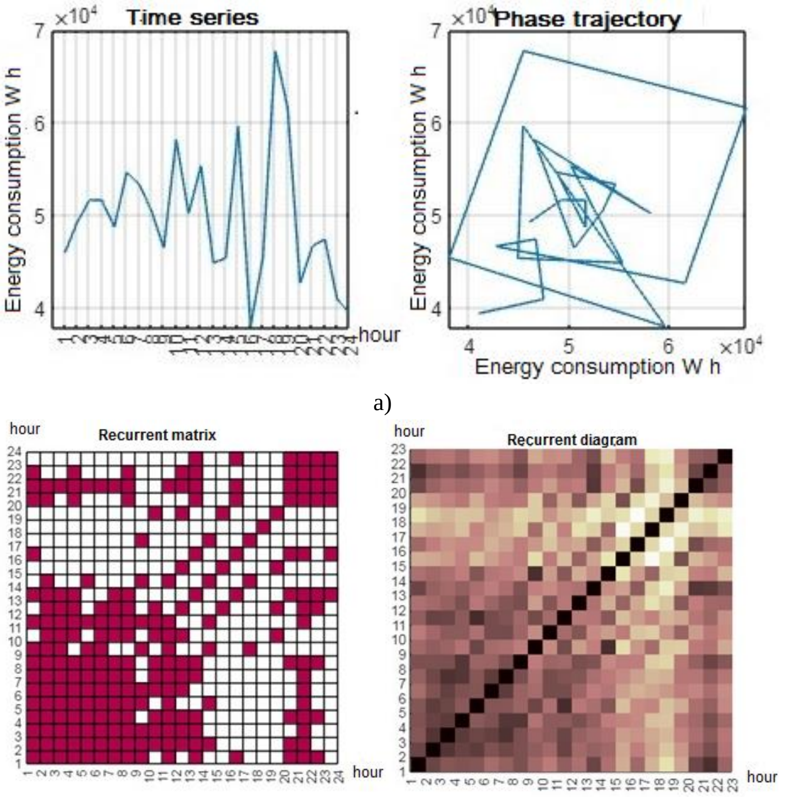
Below, in figs. 3 and 4, recurrent diagrams are shown for the time series of winter and summer seasons. They are based on the average daily energy consumption for winter and summer in 2018–2021.

The recurrent diagrams in figs. 1–4 make it possible to distinguish contrasting areas corresponding to sharp changes in the system dynamics.

For a more detailed study of the obtained recurrent diagrams, we developed *Matlab* software that automates the calculation of quantitative indicators of the formed structures of recurrent diagrams for given time series. To calculate the quantitative measures, the values of $l_{\min} = \nu_{\min} = 2$ are taken.

With the help of the developed software in the *Matlab* environment, the process of energy consumption at a metallurgical enterprise was analyzed and the dynamics of its quantitative indicators was evaluated (Table 1).

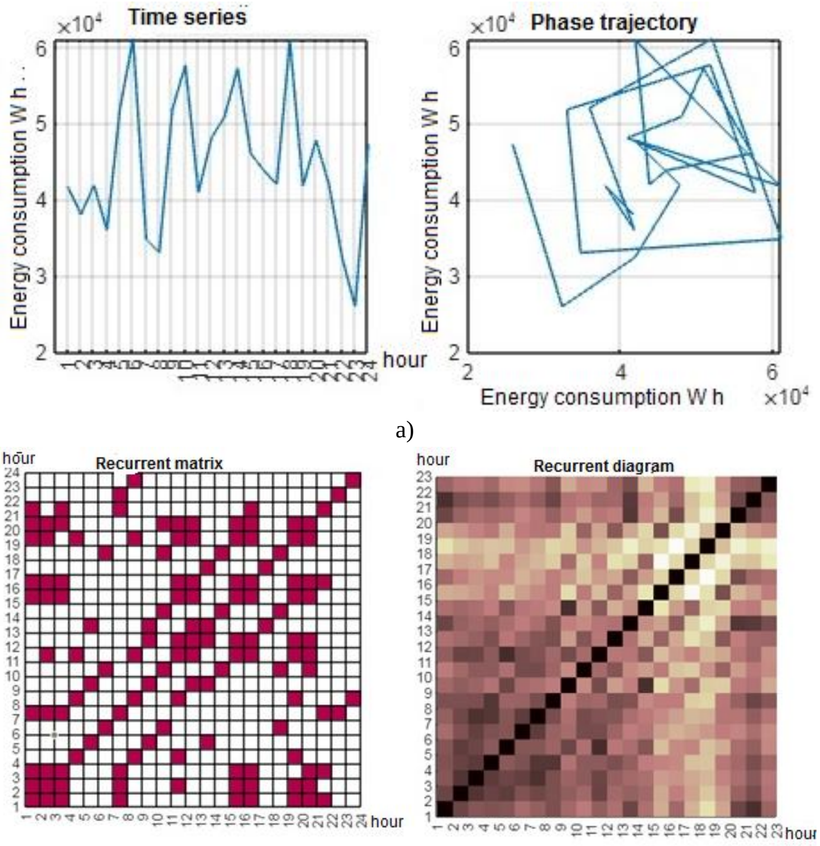
Given the results obtained, we also analyzed the dynamics of the quantitative indicators of the system over time, since the dynamics of the calculated complexity measures is an indicator of changes in the state of the system. The graphs shown in figs. 5 and 6 show the dynamics of quantitative measures by days of the month for the winter and summer periods, respectively.



a)

b)

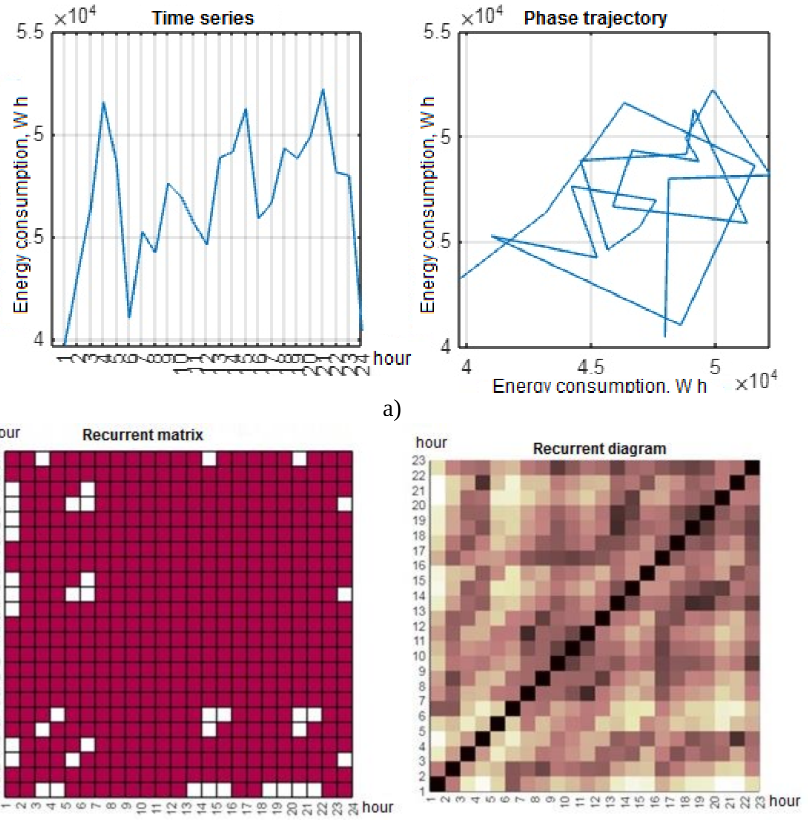
Fig. 1. Recurrent daily diagrams built in *Matlab* for February 04, 2021



a)

b)

Fig. 2. Recurrent daily diagrams built in *Matlab* for July 04, 2021



a)

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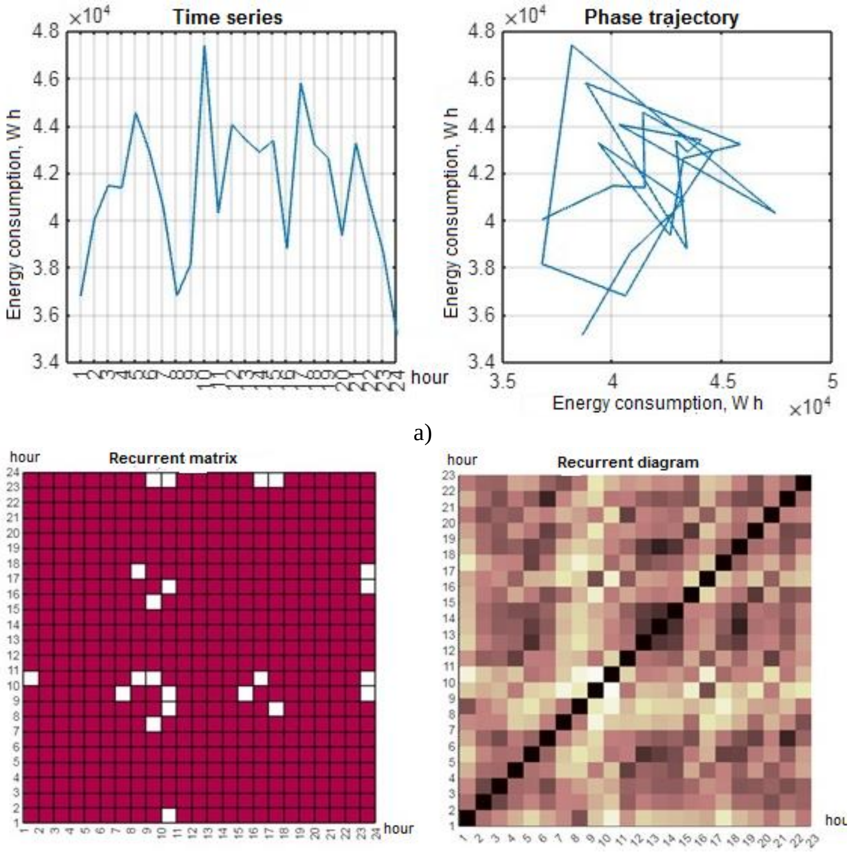
Fig. 3. Recurrent charts built in *Matlab* for the winter period (2018–2021)



a)

b)

Fig. 4. Recurrent charts built in *Matlab* for the summer period (2018–2021)

Table 1. *Indicators of quantitative analysis of recurrent charts*

	RR	DET	L	DIV	ENTR	RATIO	LAM	TT
winter period								
2018	0,3791	0,7728	3,2907	0,1452	10,0034	4,4158	0,7141	3,2484
2019	0,4118	0,8211	3,2966	0,1467	11,898	3,7866	0,7455	3,4923
2020	0,3675	0,9543	7,6927	0,0434	23,9239	3,0806	0,9351	10,0549
2021	0,4386	0,8109	3,2660	0,1462	12,7020	3,7324	0,7369	3,4523
summer period								
2018	0,2959	0,7872	2,2999	0,1627	8,9675	5,5494	0,6606	3,1756
2019	0,3598	0,9548	7,9089	0,0435	23,1336	3,1477	0,9206	10,3593
2020	0,3770	0,9669	7,9860	0,0435	23,0838	3,013	0,9077	9,9727
2021	0,3491	0,9474	8,2313	0,0435	21,1106	3,2213	0,8812	10,5858

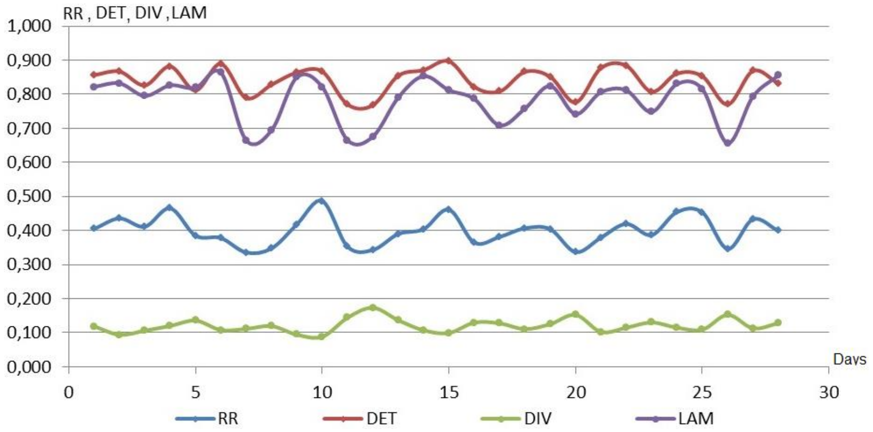


Fig. 5. Dynamics of changes in quantitative measures over the winter period

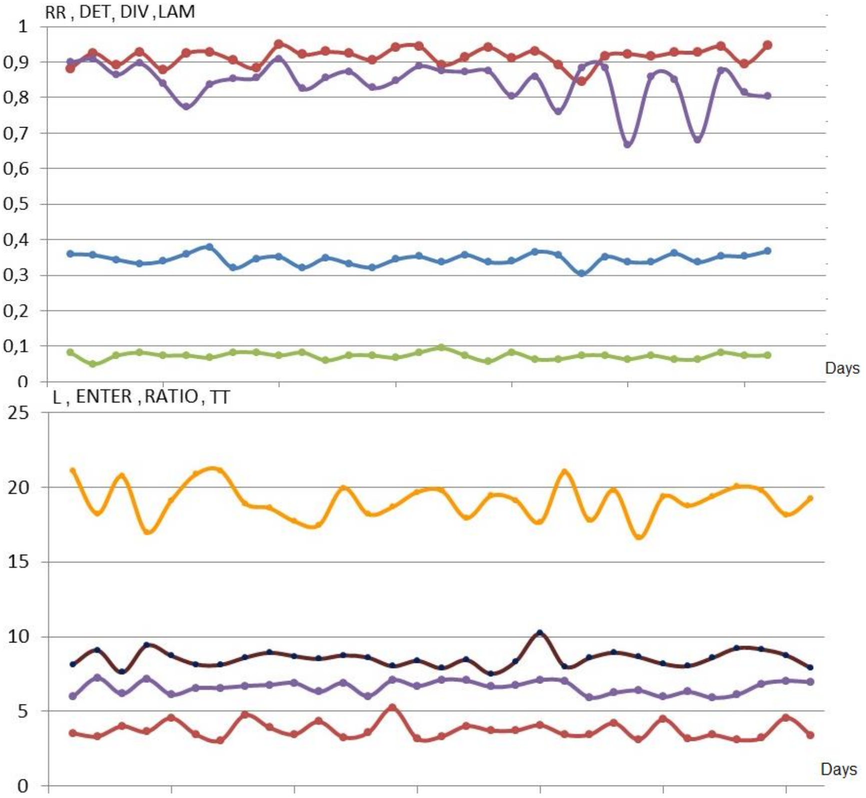


Fig. 6. Dynamics of changes in quantitative measures over the summer period

These graphs show that the measures calculated for the set of recurrent diagrams are quite stable. This confirms the thesis about the presence of a deterministic component in the system, which is determined by the technological features of the enterprise's production processes.

Discussion

Using the developed software in the *Matlab* environment, we analyzed energy consumption based on observations of the complex dynamic system of hourly electricity consumption of PrJSC "Dneprospetsstal" for four years and evaluated the dynamics of quantitative indicators of the corresponding recurrent diagrams [16].

As noted earlier, in recurrent analysis, an essential feature characterizing deterministic processes is the presence of lines parallel to the main diagonal. The greater the number of points on the diagonal lines, the greater the deterministic component of the series. The quantitative rates DET, DIV and $ENTR$, described by equations (6), (8), and (9), respectively, are based on this fact. The average length of the diagonal lines L (16) is also a meaningful measure, because it takes into account the length of different lines, while DET counts all points on parallel lines regardless of their length. Thus, for purely random processes, the value DET will be very small (close to zero), while processes with some deterministic component will correspond to values of this rate that are much larger than zero (close to one). Similarly, the higher the value of L, the higher the probability that the process is deterministic.

The average values of the entropy rate and $(ENTR)$ are also quite high, which indicates the complexity of the obtained recurrence diagrams with respect to diagonal lines. Thus, we can conclude that the studied series contain a certain deterministic component, which is determined by the technological features of the enterprise's production processes. Deterministic processes result in long diagonals and a small number of individual recurrent points. The average length of the diagonal lines, which is related to the time of predictability of the dynamic system, corresponds to the value of 5.4. The average length of the vertical lines, which reflects the time during which the system remains in a certain state, corresponds to 3.8.

The average value of the laminarity rate (LAM) is also quite high, which indicates the presence of system laminarity states, i.e., when the system's movement along the phase trajectory stops or moves very slowly.

The recurrence rate (RR) is close to 0.35 on average. That is, the probability of repeating a certain state of electricity consumption during a period (month) is 35%.

Taking into account the analysis of the average values of quantitative measures in the off-season, we can see that greater predictability, as well as a much higher delay indicator, which characterizes the average time when the system can remain in a more or less unchanged state, characterize the summer period.

The application of the recurrence analysis method to the time series of electricity consumption can contribute to a positive economic effect in the future by improving the energy efficiency of a metallurgical enterprise.

Conclusion

The scientific and applied novelty of this work is the application of the method of building recurrent diagrams to the analysis of a complex dynamic system of hourly electricity consumption by a metallurgical enterprise. The method was applied to real data represented by short time series. In the course of the study, software for the construction and quantitative analysis of recurrent diagrams in the *Matlab* environment was also developed, which helped to identify patterns and obtain information about the properties of the system under study.

The practical significance of this work is the benefit of applying the recurrent analysis method to the assessment of electricity consumption, as well as modeling this process, which will help to improve the accuracy of forecasting its future dynamics.

In further research, it is planned to analyze the impact of noise in energy consumption observations on the quality of signal detection using the numerical characteristics of recurrent diagrams.

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РЕКУРЕНТНИЙ АНАЛІЗ ЕНЕРГОСПОЖИВАННЯ МЕТАЛУРГІЙНОГО ПІДПРИЄМСТВА

Предметом дослідження є моделі та методи для короткострокового прогнозування енергоспоживання в енергосистемах на основі рекурентного аналізу часових рядів. **Мета роботи** – рекурентний аналіз часових рядів енергоспоживання металургійного підприємства та розроблення програми в середовищі *Matlab* для автоматизації обчислень і експериментальне випробування доступної інформації ПрАТ "Електрометалургійний завод "Дніпроспецсталь" ім. А. М. Кузьміна". **Виконані такі завдання:** розглянуто метод побудови рекурентних діаграм та їхній кількісний аналіз; побудовано модель часового ряду та фазової траєкторії часового ряду для візуалізації зміни енергоспоживання протягом доби; розроблено програмне забезпечення для побудови рекурентних діаграм у пакеті *Matlab*. **Використано метод** аналізу часових рядів на основі рекурентного аналізу для дослідження характеристик стану системи на прикладі металургійного підприємства. **Здобуті результати**: розроблено програмне забезпечення в середовищі *Matlab* для короткострокового прогнозування енергоспоживання в енергосистемах; розраховано кількісні показники, що можна застосовувати для характеристики стану системи й аналізу енергоспоживання в міжсезоння. **Висновки:** у процесі дослідження розроблено програмне забезпечення для побудови та кількісного аналізу рекурентних діаграм у пакеті *Matlab*, за допомогою якого виявлено закономірності та отримано інформацію про властивості досліджуваної системи. З огляду на аналіз середніх значень кількісних мір у міжсезоння за 2018–2021 рр. можна бачити, що літній період визначається більшою передбачуваністю, а також значно вищим показником затримки, який характеризує середній час, коли система може залишитися в більш-менш незмінному стані. Реальними результатами підтверджено користь застосування методу рекурентного аналізу для оцінювання споживання електроенергії, а також ефективнішого моделювання цього процесу, що може сприяти більш точному прогнозуванню його майбутньої динаміки.

Ключові слова: рекурентна діаграма; енергоспоживання; часовий ряд; нелінійна динаміка.

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