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Recurrence Analysis of the Economic Behavior of Agents of the Frequency of Online Exchange Rate in the Information Environment

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ABSTRACT
The behavior of the socio-economic agents of the foreign exchange market has always been characterized by insufficient predictability, therefore today researchers do not leave the search for new methods and indicators for their prediction. With the development of the information society and online technologies, one of the manifestations of the behavior of agents in the foreign exchange market has become their semantic-thematic online queries in search engines. Considering that the time series of exchange rates have been sufficiently studied, insufficient attention has been paid to the dynamics of the frequency of requests for exchange rates as to the parameters of the online behavior of foreign exchange market agents. Since the dynamics of the frequency of requests for exchange rates (dollar, euro) is non-linear, a recurrence analysis was applied. The results of this analysis proved that the tendencies of informational activity of agents are characterized by an antipersistent type of behavior with periodicity and the presence of drift, which are manifested in varying degrees for each exchange rate. If for the indicator of the dollar exchange rate a concentration of interest of market agents near the trajectory of a certain attractor with other deviations due to other factors is shown, then a similar indicator of the euro exchange rate is characterized by a more pronounced and stable over time cyclical manifestation of information activity of agents. In further researches, it is planned to implement a quantitative analysis of the constructed recurrence plots in order to take into account the behavior of the agents of the foreign exchange market.
Keywords: *request frequency, exchange rate, dollar, euro, information activity, pseudo phase space, phase portrait, recurrence plot, behavior of socio-economic agents*

1. INTRODUCTION

The rapidly growing value of information as a special resource forms the model of the information society, therefore, the intentions of socio-economic agents regarding the management of this resource determine only their active state in the market. Information activity is characterized by the measure of dissemination of information in the external information space. Therefore, a more active use of information significantly expands the range of possibilities of a socio-economic market agent. However, the increasing potential of opportunities may not be used in the case of a wrong management decision.

The information activity of socio-economic agents of the market is an integrated parameter of the structure of the information search of various objects of online requests that can characterize the demand in the markets. That is, the information activity of socio-economic market agents acts as a parameter of the synthesized structure of their information activity and business activity. On the one hand, information activity is determined by the structure of the semantic core, that is, the semantic load of queries that determine the vector of agents' interest in one or another aspect of the market. On the other hand – the frequency of requests made in the online environment at different time intervals, periods of development of the socio-economic system and the current range of interests of agents. In addition, the greater the frequency of a particular request and its interpretations in the period t, the higher the measure of interest of the subject in this search area. The accuracy and correctness of the request forms an idea of the knowledge of the agent in a certain area of his interests, and therefore acts as the basis for the formation of a motive for his behavior in the market. Thus, the frequency of online requests is simultaneously an indicator for determining the sphere of interests of market agents, a means of monitoring demand, and the influence of its value acts as the basis for substantiating management

decisions. Frequency dynamics determines the nature of the behavior of socio-economic agents in the market.
Since cash flows provide the needs of society at all levels of the Maslow pyramid, the interest in financial instruments only increases. That is why such macroeconomic instruments as exchange rates, crypto currency, derivative financial instruments, goods, services are be increasingly relevant.
According to the principle of the interaction of supply and demand, an increase in interest in individual tools leads to an increase in the number of requests for them in Internet search systems, which leads to a corresponding increase in their prices in the markets, and thereby again leads to an increase in their popularity in society (Figure 1).
Thus, the interdependence, for example, of the exchange rate and online requests for it is cyclical and is characterized by a subjective feedback.

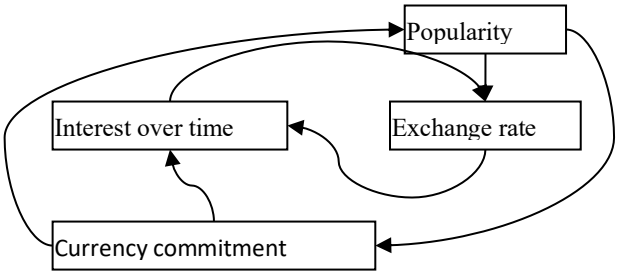

Figure 1 Logically substantiated dependence of the frequency of requests and request objects

Therefore, the purpose of this research is the information activity of socio-economic agents that operate within the information space of the foreign exchange market in terms of the frequency of requests for a definite current exchange rate of the country. The object of the research is the time series of the frequency of requests for exchange rates in Ukraine according to Google Trends. The subject of the research are the methods of nonlinear dynamics.

1.1. Related Work

Currently, the information space of the online environment is developing in conditions of an unlimited public request for relevant macroeconomic tools. At this stage of Ukraine's development, the time series of macroeconomic instruments are indicators of the socio-economic state of the country and its long-term changes, so the society is interested in them using accessible search engines. The aforesaid is confirmed by the results of studies on the interdependence of requests on social networks and bitcoin courses [1], in which the author proved the positive effect of the increasing popularity of bitcoin on the increase in the number of search queries. Also, in research [2], the necessity of taking into account the data of social networks when predicting bitcoin time series based on the weight of correlation, the presence of self-similarity, and multifractal properties of the series is confirmed. A fractal analysis of the time series dynamics of the frequency of requests for exchange rates as a macroeconomic indicator of information activity of socio-economic market agents was carried out in [3] on the basis of processing the corresponding methodology [4, 19, 20].
Thus, the research of the time series of the behavior parameters of market agents lies in the plane of nonlinear dynamics problems [5, 6, 7, 18], the object of research of which in modern scientific works is the courses of financial and electronic tools, crisis phenomena, the dynamics of the development of financial markets [8, 9, 10, 22, 23] with the aim of identifying natural trends, self-similarity, cyclicity, and other properties [11, 21]. Only the information space of the online environment remains superficially studied, although it quantitatively reflects the range of interests of agents in the markets in dynamics.

1.2. Materials

Since one of the manifestations of agents' information activity is the search for key information on parameters that are economically significant for making managerial decisions, the long-term stability of the functioning of socio-economic agents in the market completely relies on systematic monitoring these parameters.
Now the exchange rate is almost the most priority tool both at the state level and for the average citizen. The influence of price fluctuations in the currency today is felt by every business entity and members of society. So, according to serpstat.com [12] data, it has been established that according to statistics of queries in search engines, in particular Google, financial issues are most often of interest to socio-economic agents of the market. So, on September 12, 2019, there were 4400 requests for such a keyword as "economy", 33100 – "finance", 820300 – "exchange rate", of which 550,000 – "dollar exchange rate".
Thus, the interests of socio-economic agents in the online environment can also demonstrate the dynamics of query frequencies for the keywords "exchange rate", "dollar exchange rate", "euro exchange rate" (Figure 2). The constructed time series of the frequency of requests for keywords relative to exchange rates demonstrate different dynamics in different periods, which is explained by internal disturbances in the structure of the country's socio-economic system, the foreign exchange market, changes in interests, and therefore the information activity of market agents as the response to the influence of the external environment. In Figure 2 it is clearly seen that for the period 2014-2015 the information activity of the frequency of requests "exchange rates" in general and "dollar exchange rates" separately increased sharply, which is explained by the destabilization of the whole country as a result of the outbreak of the hybrid war. The identity of the trends in the frequency of requests "dollar exchange rate" and "exchange rate" is explained by a significant dolorization of the Ukrainian economy, therefore, according to the results of the seo-analysis, the

overwhelming majority of requests for exchange rates refer to the dollar exchange rate in Ukraine (Figure 3).

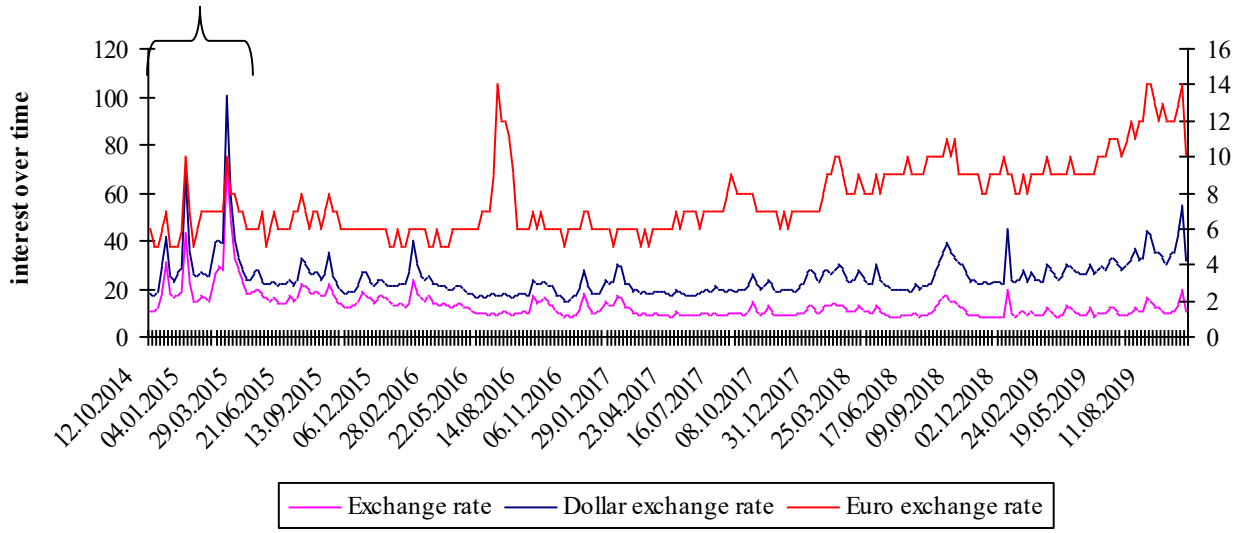

Figure 2 Frequency of requests "exchange rate", "dollar exchange rate", "euro exchange rate" on Google in Ukraine

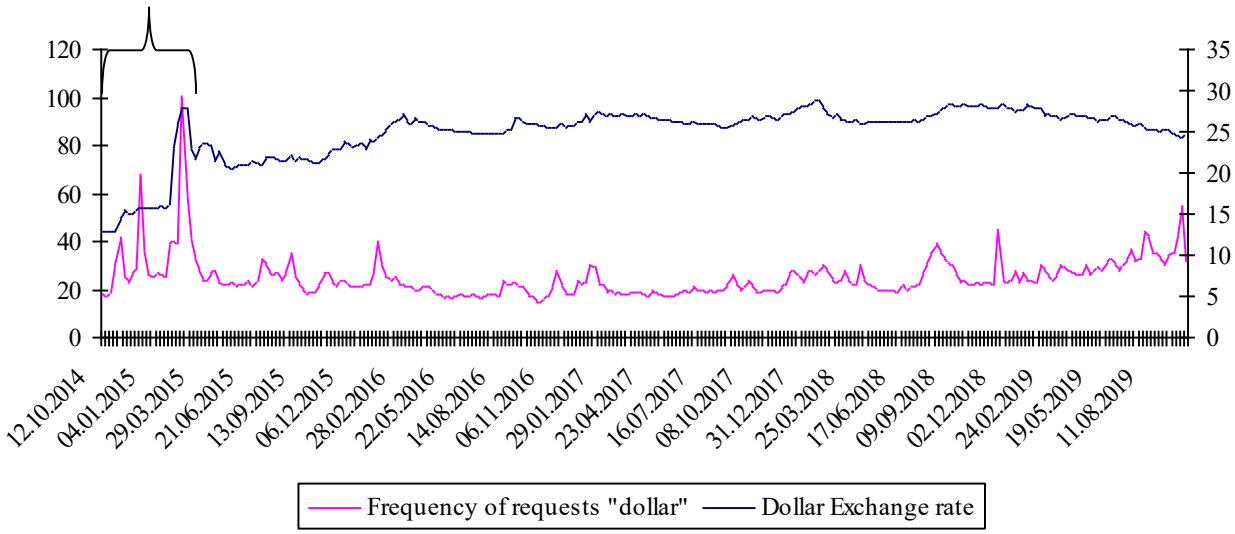

Figure 3 The frequency of requests for the keyword "dollar exchange rate" in the Google search engine and the dynamics of the dollar exchange rate in Ukraine

The relationship between the indicators in Figure 3 is formed informally, since a significantly larger number of economic factors affect the exchange rate, and socio-psychological factors affect the frequency of requests. Therefore, the statistical relationship between these indicators is low, which is confirmed by the results of the correlation analysis, which determined the absence of a linear relationship between the actual exchange rate and requests for exchange rates in the country. These results confirmed the advisability of using not statistical research methods, but nonlinear dynamics methods. The article suggests the use of methods for constructing phase portraits.

1.3. Method

To research the time series of user requests regarding exchange rates, the authors proposed a methodology for analyzing information activity (Figure 4).

The set of the initial data regarding user requests was formed with the help Google Trends over the period from October 12, 2014 to October 16, 2019. To apply the proposed methodology, the data values of the initial series were normalized in the interval [0, 1] by the formula

$$x_{norm} = \frac{x_i - x_{\max}}{x_{\max} - x_{\min}},$$

where x_{norm} – normalized time series value;

$x_{\max}$, $x_{\min}$ – maximum and minimum value of the time series, respectively.

After the formation of the set of initial data, the next step is the choice of the reasonable delay of the time series G. Choosing G should take into account the following:

– G must be large enough so that the value $x(t)$ different from the value $x(t+G)$;

– but if G is too large, then at time $(t+G)$ the system will lose information about what happened at time t.

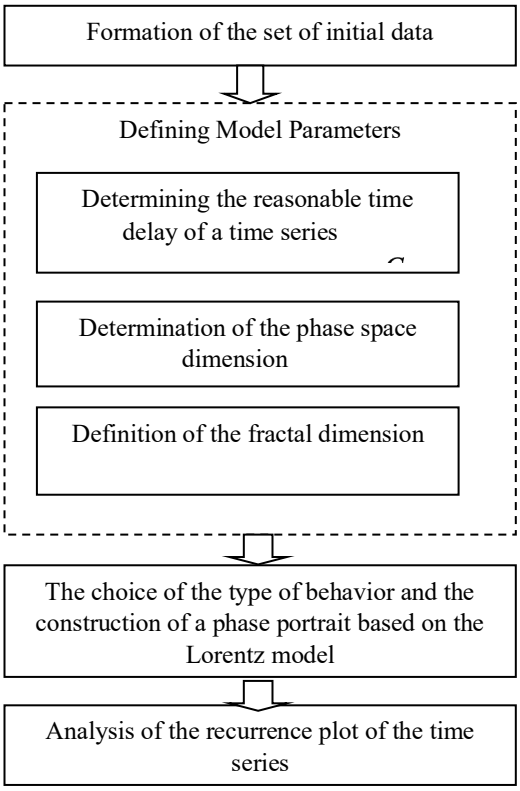

Figure 4 Methodology for the analysis of information activity of online users

Taking into account the indicated criteria for the investigated time series, a function of mutual information S [13]:

$$S = -\sum_{ij} p_{ij}(G) \cdot \ln \frac{p_{ij}(G)}{p_i p_j},$$

where S – the average mutual information;

$p_{ij}(G)$ –the joint probability that an observation falls into the i-th interval and the observation time G later falls into the j-th;

p_i – the probability to find a time series value in the i-th interval;

p_j – the probability to find a time series value in the j-th interval.

The time series delay time G corresponds to the first local minimum of the mutual information function (AMI). The time series reasonable delay time was calculated in the R environment using the *tseriesChaos* library.

The next step is to determine the dimension of the phase space (attractor) r. The optimum is the minimum dimension of the attractor, starting from which the phase trajectory gets rid of self-intersections. In determining the optimal dimension, the authors used the method of false nearest neighbor, given in [14]. This method is based on the assumption that in a correctly constructed attractor the neighboring points of the phase trajectory remain very close at the following iterations. If the nearest points diverge, then they are called false nearest neighbors. The problem is to choose a dimension of the phase space r at which the fraction of points with false neighbors is minimized.

The idea of a method for determining a false nearest neighbor is as follows: for each point $\vec{s_i}$ in the time series, we find the nearest neighbor $\vec{s_j}$ in m-dimensional space. Next, the distance between the two points $\left\|\vec{s_i} - \vec{s_j}\right\|$ is calculated and the dimension of the phase space is calculated. In order to make sure that the obtained point i is a false neighbor of the point j, it is necessary to increase the dimension of the phase space by one, that is $m = m+1$, and analyze the change in the distance between the points i and j [13]:

$$R_i = \frac{\left|s_{i+1} - s_{j+1}\right|}{\left\|\vec{s_i} - \vec{s_j}\right\|}.$$

If R_i exceeds some predetermined threshold value, then the point i is a false neighbor of the point j. This condition is checked for all points of the time series and various $ь = 2,3,\ldots$, until the fraction of points for which R_i exceeds some predetermined threshold value is reduced to zero. The calculation of false neighbors was calculated in the R environment using the *fractal* library.

To determine the fractal dimension of the studied series b, the Hurst index is first calculated according to the following algorithm [15]:

– determination of the average value of the time series

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n},$$

where n – time series length;

– determination of accumulated deviation

$$x_{\tau,t} = \sum_{i=1}^{t} (x_i - \overline{x}),$$

$$R_\tau = \max_{1 \le t \le \tau} x_{\tau,t} - \min_{1 \le t \le \tau} x_{\tau,t},$$

where $\tau = 3, 4, ..., n$,

R_τ – normalized range;

– determination of standard deviation

$$S_t = \sqrt{\frac{\sum_{i=1}^{\tau} (x_i - \overline{x})^2}{\tau}};$$

– calculation of R/S and its logarithm, as well as the logarithm of n;

– construction of R/S-trajectories, that is, a graph of the dependence of $\ln(R/S)$ on the period $\ln(n)$;

– construction of the linear regression equation, the coefficient of an independent variable in which is the Hurst indicator. Then the fractal dimension of the time series is $b = 2 - H$.

The next step in analyzing the information activity of online users (according to the methodology in Figure 4) is to build a phase portrait of the system. The phase portrait of the system is based on the Lorentz model, which is described using a system of three nonlinear differential equations:

$$\begin{cases} \dfrac{dx_t}{dt} = -G \cdot (x_t - x_{t+1}) \\ \dfrac{dx_{t+1}}{dt} = x_t \cdot x_{t+2} + r \cdot x_t - x_{t+1} \\ \dfrac{dx_{t+2}}{dt} = x_t \cdot x_{t+1} - b \cdot x_{t+2} \end{cases},$$

where x_t – the interest over time of requests (normalized values);

x_{t+1} – the interest over time of requests shifted by one period (normalized values);

x_{t+2} – the interest over time of requests shifted by two periods (normalized values);

G – the reasonable time delay of a time series;

r – the phase space dimension;

b – the fractal dimension.

The last stage of the proposed methodology is the analysis of the recurrent surface of the investigated time series. Analysis of recurrence plot makes it possible to identify small-scale structures — a texture that consists of elements such as [16]:

– isolated, that is, separately located recurrence points, appear when the corresponding states of the system are rare or unstable over time, or are caused by high turbulence;

– diagonal lines appear on the plot in the case when the trajectory repeats itself, returning to the same region of the phase space at different time periods;

– vertical (horizontal) lines identify time intervals during which the state of the system does not change or changes very slowly.

Thus, the analysis of the recurrence plot makes it possible to assess the characteristics of a nonlinear object in relatively short time series, which makes it possible to make prompt decisions regarding the control of the object [17].

2. RESULTS

The research obtained such results were relative to the delay time of the time series of the interest over time of request "dollar exchange rates" (Figure 5).

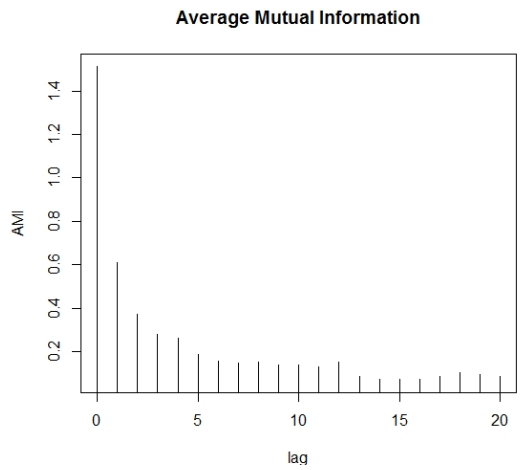

Figure 5 The mutual information function (AMI) of the time series of the interest over time of request "dollar exchange rates"

Figure 5 shows that the first local minimum of the mutual information function is achieved on the 7th period with a value of 0,14600921. This indicates that the delay time of the time series is 7 periods.

The results of determining the dependence of the fraction of false nearest neighbors on the dimension of the phase space are shown in Figure 6.

Figure 6 shows two criteria that characterize the false neighbors and the attractor:

– *rtol* provides the first criterion for classifying neighboring coordinates in phase-space as false neighbors;

– *atol* provides the second criterion for classifying neighboring coordinates in phase-space as false neighbors.

The minimum value of rtol is achieved at $r = 6$, which corresponds to the optimal phase space dimension. Also, the results of calculating the fractal dimension of the studied series proved that the indicator $b = 1,617$, which characterizes the type of behavior of socio-economic agents of the foreign exchange market in terms of the

interest over time of request "dollar exchange rates" as antipersistent.

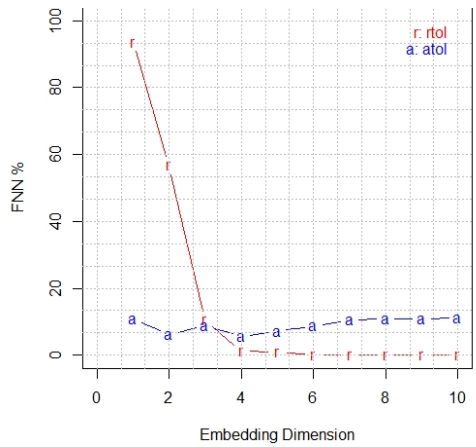

Figure 6 The percentage of false nearest neighbors for the time series of the interest over time of request "dollar exchange rates"

After determining the parameters of the nonlinear dynamic system, the corresponding phase portrait was built on the basis of the Lorentz system (Figure 7):

$$\begin{cases} \dfrac{dx_t}{dt} = -6 \cdot (x_t - x_{t+1}) \\ \dfrac{dx_{t+1}}{dt} = x_t \cdot x_{t+2} + 7 \cdot x_t - x_{t+1} \\ \dfrac{dx_{t+2}}{dt} = x_t \cdot x_{t+1} - 1{,}617 \cdot x_{t+2} \end{cases}.$$

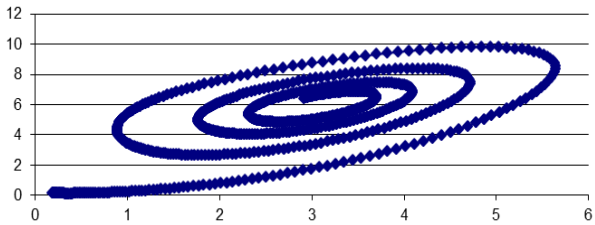

Figure 7 Phase space of behavior of socio-economic agents of the foreign exchange market in terms of the interest over time of request "dollar exchange rates"

The obtained phase portrait of the behavior of the socio-economic agents of the foreign exchange market proves that cycles can be traced, the length of which increases with time. The expansion of the diameter of the cycles is due to an increase in the concentration of attention of market agents at certain time intervals relative to the dollar, which corresponds to the characteristic state of the socio-economic system.

A recurrent plot of the time series of the interest over time of request "dollar exchange rates" is shown in Figure 8. The plot in Figure 8 indicates the chaotic behavior of the socio-economic agents of the foreign exchange market with a pronounced linear trend.

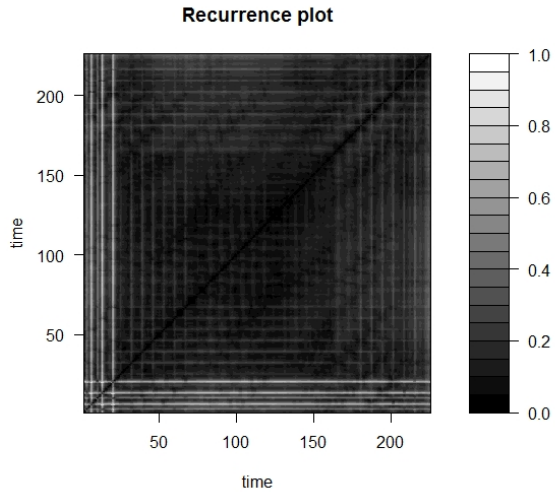

Figure 8 Recurrence plot of behavior of socio-economic agents of the foreign exchange market in terms of the interest over time of request "dollar exchange rates"

Thus, interest in the dollar is volatile, depending on a wide range of socio-economic factors. We also clearly see that the topology of recurrence plot is designated as a drift, that is, a model of the behavior of socio-economic agents of the foreign exchange market in the information space with parameters that change rather slowly over time is presented. This is proved by the white zones in the upper left and lower right corners of the recurrence plot. In addition, the presence of horizontal and vertical lines indicates a slow change in the interests of socio-economic agents regarding the dollar and their multi-layered nature. The diagonal symmetrical line is present in the recurrence plot and is the line of identity. Also, the plot contains diagonal lines that confirm the randomness of online information activity as a form of manifestation of the socio-economic agents of the foreign exchange market, since the distance between them is not the same.

Of interest is the lower left corner of the recurrence plot (Figure 9), an increase of which is shown in Figure 9. According to Figure 9, it is seen that the white vertical and diagonal lines intersect at right angles, forming a zone where the agent behavior model periodically retains its parameters. That is, their information activity is stably manifested in order to monitor the dollar exchange rate as a significant market tool for influencing the socio-economic system in which the agent operates.

Also, the present periodicity of behavior may be due to a regular revival of information activity of agents in the online environment as a result of certain socio-economic changes, as a result of which corresponding fluctuations in exchange rates are expected.

White perpendicular lines emerge from the clearly defined square area of the plot, which proves the presence of abrupt changes in the behavior of market agents, which cause extreme and random bursts of information activity of market agents in certain periods, the explanations of which require a fundamental analysis of both the foreign

exchange market and the state of socio-economic system as a whole.

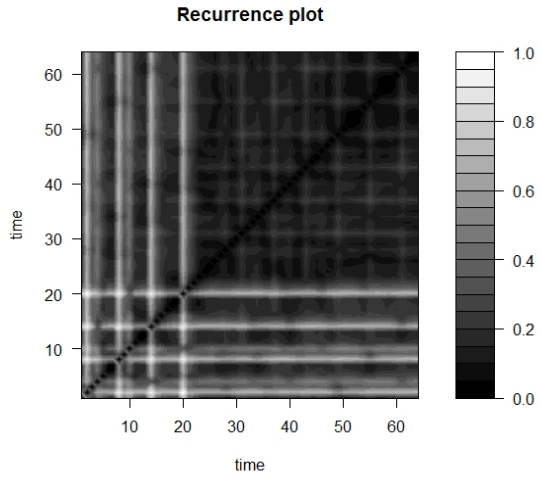

Figure 9 Recurrence plot of behavior of socio-economic agents of the foreign exchange market in terms of the interest over time of request "dollar exchange rates" (increase in scale)

The research also obtained such results were relative to the delay time of the time series of the interest over time of request "euro exchange rates" (Figure 10).

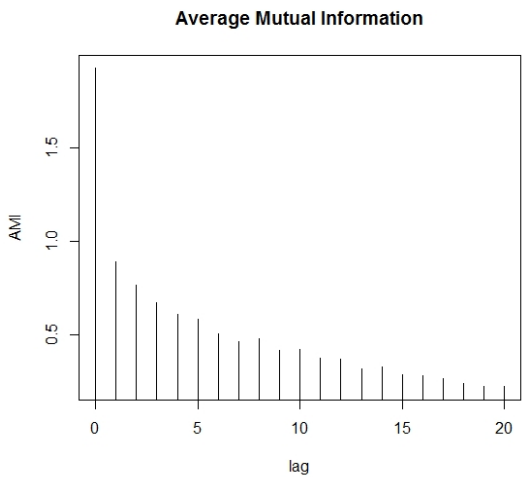

Figure 10 The mutual information function (AMI) of the time series of the interest over time of request "euro exchange rates"

Figure 10 shows that the first local minimum of the mutual information function is achieved on the 7th period with a value of 0,4604063. This indicates that the delay time of the time series is 7 periods.
Further, the results of determining the dependence of the fraction of false nearest neighbors on the dimension of the phase space are shown in Figure 11.

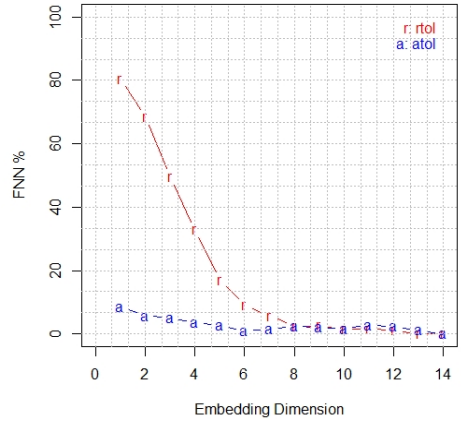

Figure 11 The percentage of false nearest neighbors for the time series of the interest over time of request "euro exchange rates"

The minimum value of rtol is achieved at $r = 13$, which corresponds to the optimal phase space dimension. Also, the results of calculating the fractal dimension of the studied series proved that the indicator $b = 1,752$, which characterizes that the type of behavior of socio-economic agents of the foreign exchange market in terms of the interest over time of request "euro exchange rates" also as antipersistent.
After determining the parameters of the nonlinear dynamic system, the corresponding phase portrait was built on the basis of the Lorentz system (Figure 12). In Figure 12, the constructed phase portrait of the interest over time of request "euro exchange rates", as in Figure 7, proves that the phase trajectories correspond to some unstable cycles.

$$\begin{cases} \dfrac{dx_t}{dt} = -13 \cdot (x_t - x_{t+1}) \\ \dfrac{dx_{t+1}}{dt} = x_t \cdot x_{t+2} + 7 \cdot x_t - x_{t+1} \\ \dfrac{dx_{t+2}}{dt} = x_t \cdot x_{t+1} - 1,752 \cdot x_{t+2} \end{cases}.$$

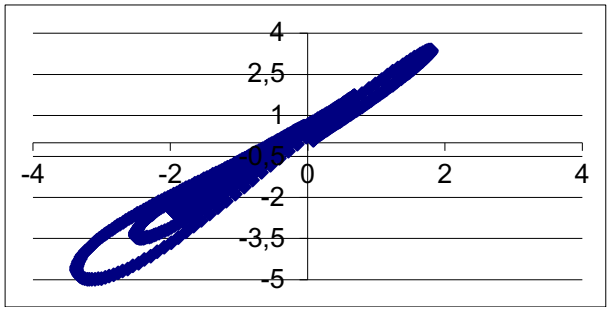

Figure 12 Phase space of behavior of socio-economic agents of the foreign exchange market in terms of the interest over time of request "euro exchange rates"

If the information activity of agents is observed within the boundaries of the cycle, then their interest in parameters will approach their equilibrium values, if from the outside,

the information activity of agents is sprayed or diverges with time. In the event of significant deviations from the equilibrium state of the system, that is, from the boundary cycle, self-oscillations of the request frequency during for a period until which the trend does not stabilize. In order to clarify the properties and establish their differences, the recurrence plot of the time series of the interest over time of request "euro exchange rates"(Figure 13).

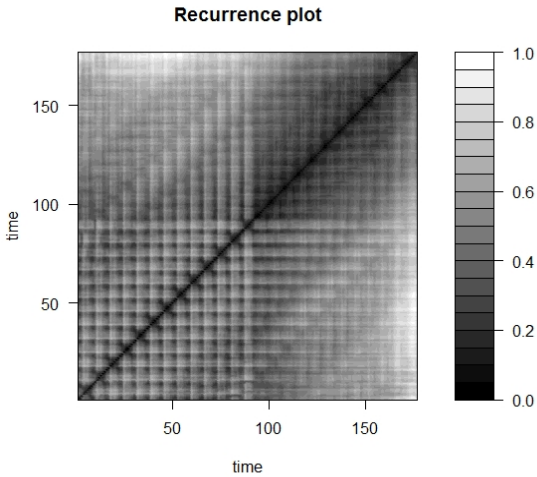

Figure 13 Recurrence plot of behavior of socio-economic agents of the foreign exchange market in terms of the interest over time of request "euro exchange rates"

The recurrence plot in Figure 13 contains periodic structures (patterns in a checkerboard pattern), which indicates a pronounced periodicity of the system in dynamics. There are also sharp changes in the dynamics of the system on the plot, which is illustrated by the corresponding changes in white areas and stripes. The structure of the recurrence diagram clearly demonstrates the cyclicality, self-similarity and repeatability of the time series of the interest over time of request "euro exchange rates", which is preserved in time than the time series of the interest over time of request "dollar exchange rates".

3. CONCLUSION

As a result of a recurrent analysis of the behavior of the socio-economic agents of the foreign exchange market in the online information environment, the following behavior of agents based on the query indicators of the exchange rate of key currencies is established. Online information requests really act as an indicator that characterizes the interests of agents in the market, their frequency determines the level of information activity in certain periods, and their dynamics – the nature of agents' behavior against the background of the state of the socio-economic system. Despite the absence of a statistical connection between the exchange rate and the frequency of its requests in the online environment, there is a logical connection between the indicators, due to subjective factors in the formation of demand for certain financial instruments and condition of the socio-economic system in which the agent operates and develops.

Common for the studied series of frequency requests for exchange rates (dollar and euro) in Ukraine was ascertained:

– the value of fractal dimension, according to which the type of behavior of socio-economic agents of the foreign exchange market is antipersistent;

– time delay time series is seven periods (days);

– phase portraits define their trajectories as unstable limit cycles;

– according to recurrence diagrams, the presence of periodicity, drift, randomness, but in varying degrees of manifestation.

However, according to the query rate indicator "dollar exchange rate", the attention of agents is traced in certain periods of time with sharp deviations during the period of socio-economic changes. That is, the behavior pattern of agents as a whole approaches equilibrium values, but with certain exceptions. This is because the Ukrainian economy is still quite closely tied to the dollar.

Whereas a similar indicator for the euro exchange rate stably demonstrates a pronounced cyclicality, a more pronounced cycle repeatability over time. The attractor drift testifies to the steadily present and gradually increasing interest of market agents by the euro exchange rate during all periods of development of the socio-economic system. For the Ukrainian foreign exchange market, the euro often acts as a stash currency. This currency change trends are smoother than that of the dollar during the crisis, therefore, with destabilization of exchange rate fluctuations and, accordingly, demand for the currency, interests regarding the euro exchange rate are stably preserved over time, since the tool is perceived as a safer alternative.

Thus, the chaotic behavior of the agents of the foreign exchange market in the information space is due to both the instability of exchange rate fluctuations, the country's economy depending on the dollar, and the specifics of the formation of their interests in relation to individual currencies during certain periods of the development of the socio-economic system. The specified specificity is explained by the demographic parameters of the contingent of stakeholders formed in the online information environment, the level of their financial literacy and awareness of financial and economic issues.

The prospect of a subsequent study is to conduct a quantitative analysis of the constructed recurrence plots in order to clarify the behavior properties of currency market agents in an online information environment.

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