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ADDITIVE MATHEMATICAL MODEL OF GAS CONSUMPTION PROCESS

Iaroslav Lytvynenko; Serhii Lupenko; Oleh Nazarevych; Hryhorii Shymchuk; Volodymyr Hotovych

Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine

***Summary**. The problem of construction of a new mathematical model of the gas consumption process is considered in this paper. The new mathematical model is presented as an additive mixture of three components: cyclic random process, trend component and stochastic residue. The process of obtaining three components is carried out on the basis of caterpillar method, thus obtaining ten components of singular decomposition. In this approach, the cyclic component is formed from the sum of nine components of the schedule, which have one thing in common – repeated deployment over time. The trend component of the new mathematical model is the second component of singular decomposition, and the stochastic residue is formed on the basis of the difference between the values of the studied gas consumption process and the sum of cyclic and trend components. Two approaches to stochastic processing of cyclic gas consumption process based on the known model of stochastic-periodic random process and cyclic random process as models of the cyclic component are used in this paper. Application of mathematical model of cyclic component in the form of cyclic random process with cyclic structure makes it possible to obtain estimation of variance on cycle of gas consumption process, provided segmentation of cyclic component on depressions, much less in comparison of obtained variance estimation for indicating greater accuracy in the study of the gas consumption process and will use the obtained stochastic estimates when modeling the gas consumption process in further studies.*

***Key words**: cyclic random process, gas consumption process, statistical processing, segmentation, cyclic random process.*

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Statement of the problem. At the present stage of development of science and technology, one of the main problem is the need for efficient use of natural resources, including energy resources, which by their nature are exhaustible, limited. This problem is especially important while using natural gas. The important task of gas supply companies is the distribution and control of natural gas consumption, which saves expensive energy resources. This is possible due to effective information systems that monitor, control and annually forecast natural gas consumption. The use of new hardware and software systems or the modernization of old ones due to the use of effective software in decision-making systems will allow us to see and analyze possible ways of natural gas saving. Such approaches can be implemented by constructing mathematical models and methods of processing the gas consumption process, taking into account the effects of various factors, such as climatic conditions, which have significant impact on the process of gas supply to the population.

Analysis of available investigation results. The topology of natural gas consumption is complex, it depends on the influence of various factors, as well as the external environment. Numerous papers concerning the development of gas consumption processes use two approaches for the construction of mathematical models – deterministic and stochastic. In published works, methods for predicting natural gas consumption are investigated using various tools and techniques. Various models are used to predict natural gas consumption, including Hubbert curve model, neural network model, statistical models, Gray prediction model, econometric model, Stochastic model of Gompertz innovation diffusion, dynamic system model and others. The authors in paper [1] using stochastic approach have developed the model

Corresponding author: Hryhorii Shymchuk; e-mail: gorych@gmail.com

in the form of linear periodic random process, which describes the energy load and makes it possible to take into account the rhythm of this process. Also in paper [2] the model of loads of the gas supply system in the form of linear periodic random process is described. In papers [3, 4] the model of Hubbert curve is presented. This model can be used to simulate the logistics function, and particularly to predict natural gas consumption. By processing information using artificial neural network, it is possible to predict the consumption of natural gas as shown in papers [5–7]. The approach in which statistical models are used for forecasting is also known [8]. In paper [9], the investigation using econometric modeling to predict natural gas consumption is described, and in [10], Bayesian averaging model (BAM) is used.

The objective of the paper. This paper is devoted to the development of mathematical model of gas consumption process based on the stochastic approach in the form of additive mixture of components: cyclic random process, trend component and stochastic residue.

Statement of the problem. In order to construct a new mathematical model of the gas consumption process, first of all let us consider the mathematical model in the form of cyclic random process, as it will be used as its component. In paper [11] the mathematical model which makes it possible to describe cyclic signals in the form of cyclic random process is substantiated. This model, as a partial case, includes the model in the form of stochastic-periodic random process considered in paper [12]. According to paper [11], a separable random process $\{\xi(\omega,t), \omega \in \mathbf{\Omega}, t \in \mathbf{R}\}$ is called cyclic random process if there is function $T(t,n)$ that satisfies the conditions of the rhythm function, i.e. conditions (1), (2), that are finite-dimensional vectors ($\xi(\omega,t_1)$, $\xi(\omega,t_2)$,..., $\xi(\omega,t_k)$) and ($\xi(\omega,t_1+T(t_1,n))$, $\xi(\omega,t_2+T(t_2,n)))$,..., $\xi(\omega,t_k+T(t_k,n))$), $n \in \mathbf{Z}$, where $\{t_1, \ t_2,...,t_k\}$ is the set of separability of the process $\{\xi(\omega,t), \omega \in \mathbf{\Omega}, t \in \mathbf{R}\}$, for all integers $k \geq 1$ are stochastically equivalent in broad sense.

Rhythm function $T(t,n)$ determines the law of change of time intervals between single-phase values of the cyclic function.

Function $T(t,n)$ should satisfy the following properties.

It is given on the whole real axis $t \in \mathbf{R}$ and on the whole set of integers and is equal to zero when $n = 0$. In other cases, it is either positive or negative, i.e.:

$$\begin{aligned} &\text{a) } T(t,n) > 0, \text{ if } n > 0; \\ &\text{b) } T(t,n) = 0, \text{ if } n = 0; \\ &\text{c) } T(t,n) < 0, \text{ if } n < 0. \end{aligned} \tag{1}$$

For any $t_1 \in \mathbf{R}$ and $t_2 \in \mathbf{R}$ for which $t_2 > t_1$ the inequality for function $T(t,n)$ is:

$$t_1 + T(t_1,n) < t_2 + T(t_2,n), \forall n \in \mathbf{Z} \tag{2}$$

The cyclic random process of continuous argument is characterized by the fact that the family of its consistent distribution functions satisfies the following equality:

$$\begin{gathered} F_{k_\xi}(x_1,...,x_k,t_1,...,t_k) = \\ = F_{k_\xi}(x_1,...,x_k,t_1+T(t_1,n),...,t_k+T(t_k,n)), \\ x_1,...,x_k,t_1,...,t_k \in \mathbf{R},\ n \in \mathbf{Z},\ k \in \mathbf{N} \end{gathered} \tag{3}$$

Mathematical model. Now let us represent the mathematical model of the cyclic process of gas consumption $\xi'(\omega,t)$ in the form of additive model consisting of three components (4). As noted above, the similar approach is used in paper [13], but let us specify the components of the new mathematical model. The additive model describing the cyclic unfolding during the gas consumption process is presented in the form of cyclic random process, in contrast to the proposed approach in paper [13] when the given component of the model is considered as stochastic-periodic random process:

$$\begin{gathered} \xi'(\omega,t)=\xi(\omega,t)+f_{tr}(t)+f_{rem}(\omega'',t), \\ t\in\mathbf{W},\omega\in\mathbf{\Omega},\omega''\in\mathbf{\Omega}'', \end{gathered} \tag{4}$$

where $\xi(\omega,t)$ is cyclic component, $f_{tr}(t)$ is trend function, $f_{rem}(\omega'',t)$ is stochastic balance function.

Since in practice we are dealing with discrete data, let us represent the mathematical model (3) in the following way:

$$\xi'_{\omega}(l)=\xi_{\omega}(l)+f_{tr}(l)+f_{rem\omega''}(l),\ l\in\mathbf{W}=\mathbf{D} \tag{5}$$

where $\xi_{\omega}(l)$ is implementation of the cyclic component of gas consumption process, $f_{tr}(l)$ is trend function, $f_{rem\omega''}(l)$ is stochastic balance function, l – discrete samples of gas consumption process, L – number of samples of gas consumption process of the registered implementation.

In order to obtain the components of mathematical model (4) in the study of real cyclic process of gas consumption $\xi'_{\omega}(l), l=\overline{1,L}$, let us use the method of Caterpillar-SSA. This method describes the transformation of one-dimensional time series into multidimensional one, which makes it possible to apply the principal components method to obtain multidimensional time series [14].

When applying Caterpillar method, we obtain k – implementation of components $\left\{\bar{f}_k(l), k=\overline{0,K-1}, l=\overline{1,L}\right\}$, where $K=10$, l – parts of the gas consumption process during 2006–2019, L – the number of discrete implementation samples.

The cyclic component is obtained by summing the components obtained on the basis of Caterpillar method particularly components: 0–1, 3–9, component 2 is trend component:

$$\xi_{\omega}(l)=\sum_{k=0}^{1}\bar{f}_k(l)+\sum_{k=3}^{9}\bar{f}_k(l),\ l=\overline{1,L}, \tag{6}$$

$$f_{tr}(l)=\bar{f}_2(l),\ l=\overline{1,L}. \tag{7}$$

The stochastic residue is obtained on the basis of the ratio:

$$f_{rem\omega''}(l)=\xi'_{\omega}(l)-(\xi_{\omega}(l)+f_{tr}(l)),\ l=\overline{1,L} \tag{8}$$

Let us consider in detail $\xi_{\omega}(l)$ – the component of the mathematical model (5), which carries information about the process of gas consumption. Let us represent it in the following form:

$$\xi_{\omega}(l)=\sum_{i=1}^{C}f_i(l),\ l\in\mathbf{W} \tag{9}$$

where C is the number of segments-cycles of the cyclic process of gas consumption, $\mathbf{W}$ is the area of determination of the cyclic process of gas consumption, and the area of its values, for the stochastic approach is Hilbert space of random variables given in one probability space $(\xi_\omega(l)\in \mathbf{\Psi}=\mathbf{L}_2(\mathbf{\Omega},\mathbf{P}))$. In structure (9) segments-cycles $f_i(l)$ of the cyclic process of gas consumption are determined by indicator functions, i.e.:

$$f_i(l)=\xi_\omega(l)\cdot I_{\mathbf{W}_i}(l),\ i=\overline{1,C},\ \ l\in \mathbf{W} \tag{10}$$

In this casethe indicator functions that allocate segments-cycles are defined as:

$$I_{\mathbf{W}_i}(l)=\begin{cases}1,\ l\in \mathbf{W}_i,\\ 0,\ l\notin \mathbf{W}_i.\end{cases},\ i=\overline{1,C}, \tag{11}$$

where $\mathbf{W}_i$ is the area of determination of the indicator function, which in the case of discrete signal, i.e. $\mathbf{W}=\mathbf{D}$, equal to discrete set of samples:

$$\mathbf{W}_i=\{l_{i,j},\ j=\overline{1,J}\},\ i=\overline{1,C}, \tag{12}$$

The segmental cyclic structure $\hat{\mathbf{D}}_c$ is taken into account by the set of time samples $\{l_i\}$ or $\{l_{i,j}\}, i=\overline{1,C}$, $j=\overline{1,J}$, where J is the number of discrete samples in the cycle. This notation of the mathematical model (9) takes into account the rhythm of the cyclic process of gas consumption through continuous rhythm function $T(l,n)$, namely:

$$I_{\mathbf{W}_i}(l)=I_{\mathbf{W}_{i+n}}(l+T(l,n)),\ i=\overline{1,C}, n=1, l\in \mathbf{W}. \tag{13}$$

Taking into account the stochastic-periodic approach (as mathematical model of the cyclic component), the indicator function will take into account period – T and is as follows:

$$I_{\mathbf{W}_i}(l)=I_{\mathbf{W}_{i+T}}(l+n\cdot T),\ i=\overline{1,C}, n=1, l\in \mathbf{W}. \tag{14}$$

In order to assess the rhythm function $T(l,n)$, the segmental structure of gas consumption process (in this case the segmental cyclic structure) is determined first as $\hat{\mathbf{D}}_c=\{l_i, i=\overline{1,C}\}$ being a set of time moments that correspond to the boundaries of the segments-cycles of the gas consumption process. The estimation of the segmental cyclic structure of the gas consumption process can be carried out using the segmentation methods presented in paper [15].

In the course of the research the segmental structure $\hat{\mathbf{D}}_c$ and estimation of the rhythmic structure (discrete rhythm function $T(l,n)$) are obtained by the methods proposed in papers [16–18]. Methods of statistical processing taking into account the rhythm function are also used [16–18].

Evaluation of mathematical expectation:

$$\hat{m}_{\xi_{T(l,n)}}(l)=\frac{1}{M}\sum_{n=1}^{M}\xi_\omega(l+T(l,n)),\quad l\in \mathbf{W}_1=[l_1,l_2) \tag{15}$$

where $l_1\neq 0$ is in the general case, l_1,l_2 are discrete time samples that correspond to the beginning and end of the first segment-cycle, M is the number of cycles.

Estimation of variance:

$$\hat{d}_{\xi_{T(l,n)}}(l) = \frac{1}{M}\cdot\sum_{n=1}^{M}\begin{bmatrix}\xi_{\omega}(l+T(l,n))- \\ -\hat{m}_{\xi_{T(l,n)}}(l+T(l,n))\end{bmatrix}^2, \quad l \in \mathbf{W}_1 = [l_1, l_2) \tag{16}$$

To compare the results of statistical processing based on the model in the form of a cyclic random process, we will also conduct statistical processing based on the stochastic-periodic approach to processing the cyclic component of gas consumption taking into account the period.

Assessment of mathematical expectation:

In order to compare the results of statistical processing based on the model in the form of cyclic random process, we also carry out statistical processing based on the stochastic-periodic approach to processing the cyclic component of gas consumption taking into account period T while statistical estimates are the following:

Assessment of mathematical expectation:

$$\hat{m}_{\xi_T}(l) = \frac{1}{M}\sum_{l=1}^{M}\xi_{\omega}(l+n\cdot T), l \in \mathbf{W} \tag{17}$$

Estimation of variance:

$$\hat{d}_{\xi_T}(l) = \frac{1}{M}\cdot\sum_{n=1}^{M}\left[\xi_{\omega}(l+n\cdot T) - \hat{m}_{\xi_T}(l+n\cdot T)\right]^2, \quad l \in \mathbf{W}, \tag{18}$$

where T is the value of the period estimated by the known method [19]; n is the value of the multiple period.

Applying the methods of statistical processing, statistical estimates of probabilistic characteristics are obtained (mathematical expectation $\hat{m}_{\xi_{T(l,n)}}(l), l \in \mathbf{W}_1$ and variance $\hat{d}_{\xi_{T(l,n)}}(l), l \in \mathbf{W}_1$ based on rhythm function $T(l,n)$ and $\hat{m}_{\xi_T}(l)$, $\hat{d}_{\xi_T}(l)$, based on period) of the cyclic process of gas consumption (Fig. 5–8).

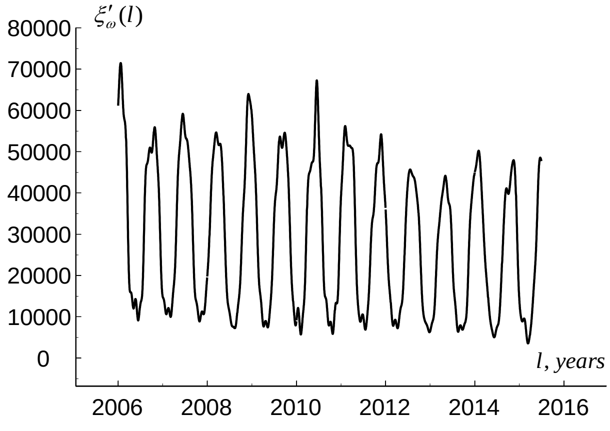
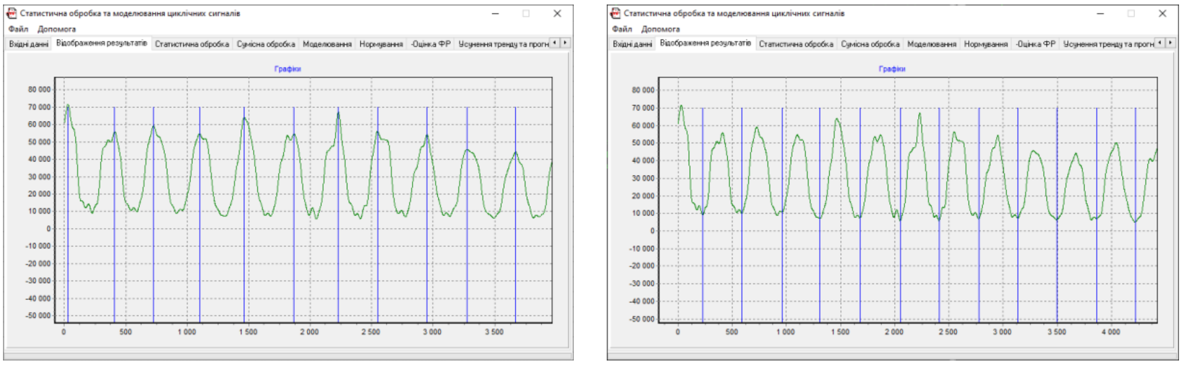
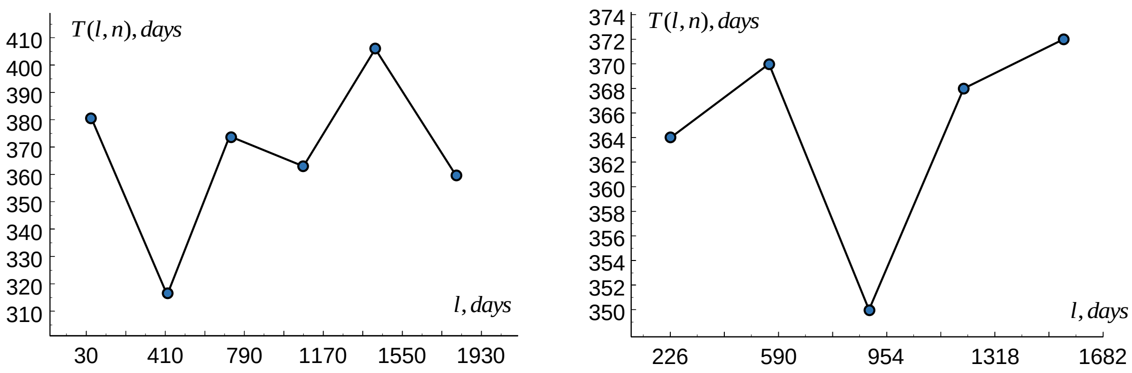


Figure 1. Input implementation (cyclic component) of the cyclic process of gas consumption



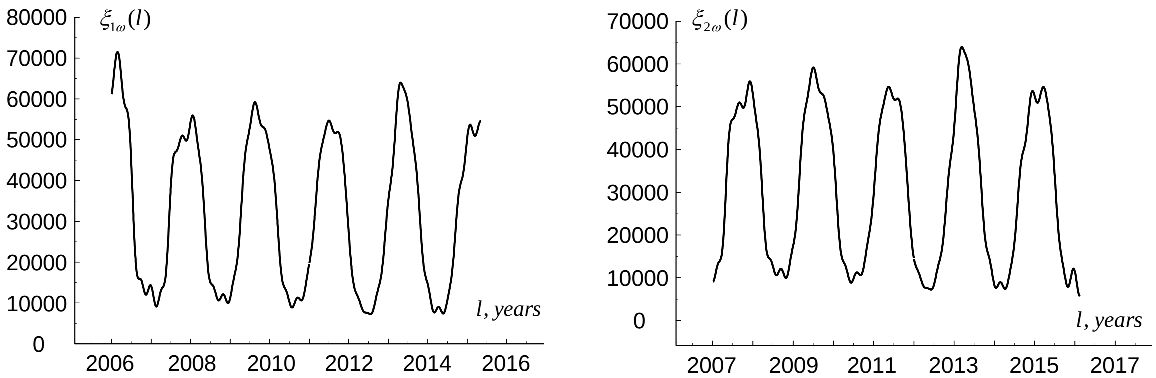
a) b)

Figure 2. The results of segmentation of the cyclic process of gas consumption:
a) based on segmentation into vertex cycles; b) based on segmentation into cycles by depressions
(abscissa axis data are given in conventional units)



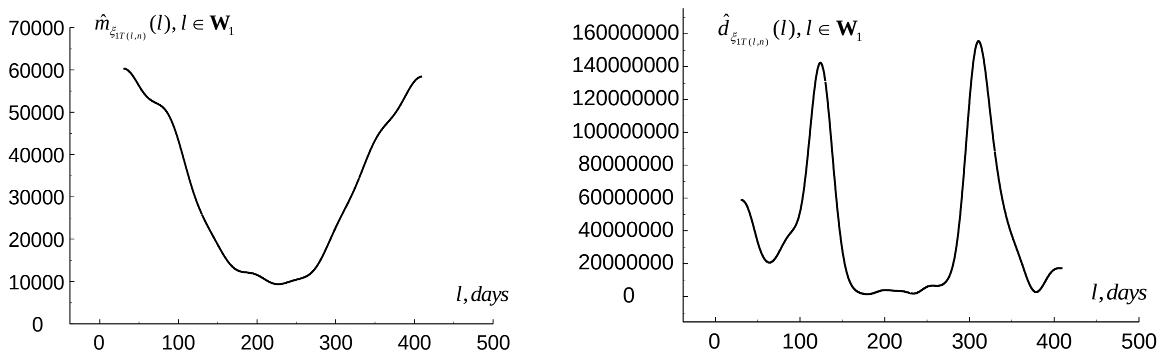
a) b)

Figure 3. Fragments of the results of the estimated rhythm function (piecewise linear interpolation)
of the cyclic process of gas consumption: a) based on segmentation into vertex cycles;
b) based on segmentation into cycles by depressions



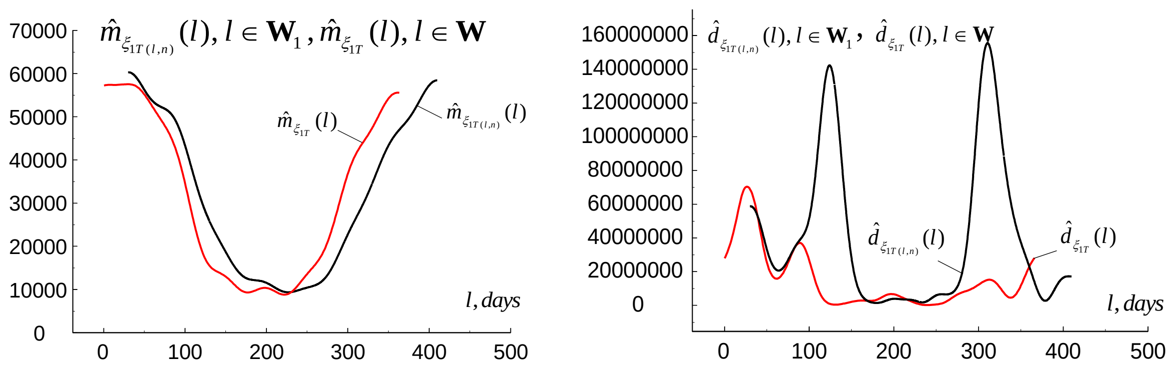
a) b)

Figure 4. Fragments of the investigated implementations of the gas consumption process:
a) for the case of segmentation by vertices; b) for the case of segmentation by depressions



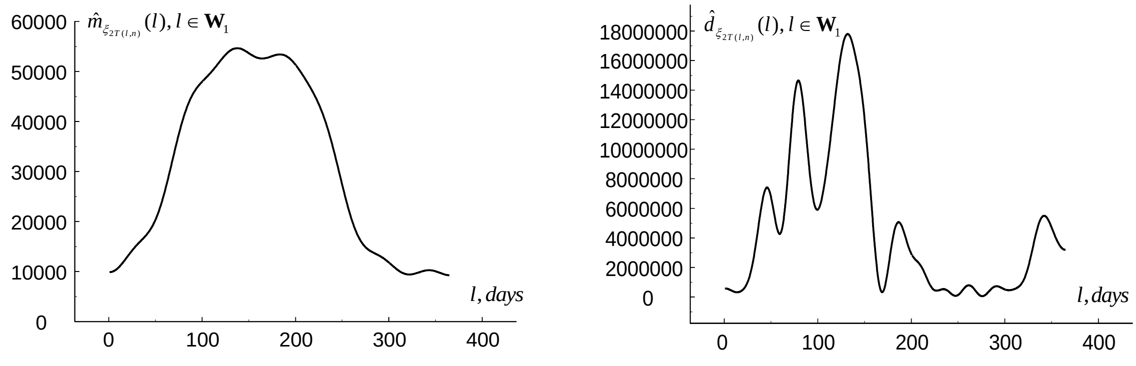
a) b)

Figure 5. Estimation of mathematical expectation and variance on the basis of taking into account the estimated function of the rhythm of the cyclic process of gas consumption (segmentation into cycles on the vertices): a) estimation of mathematical expectation; b) estimation of variance



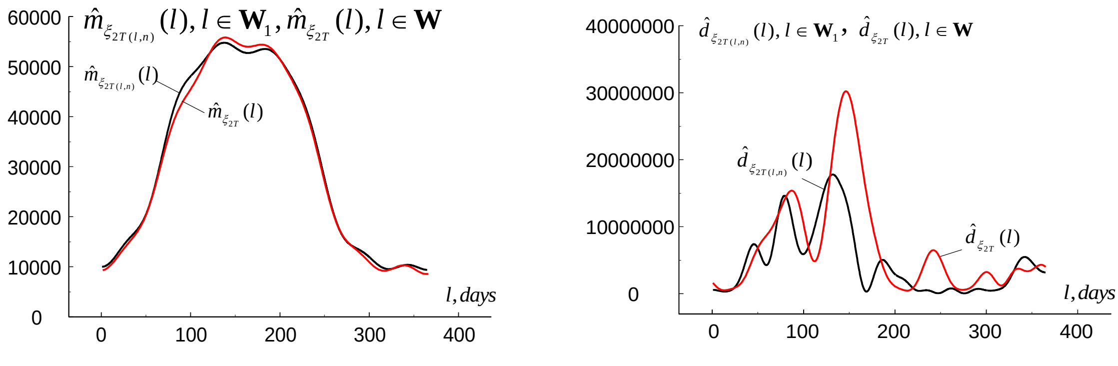
a) b)

Figure 6. Estimation of mathematical expectation and variance based on the period of the cyclic process of gas consumption for implementation (Fig. 4, a): a) estimation of mathematical expectation; b) estimation of variance



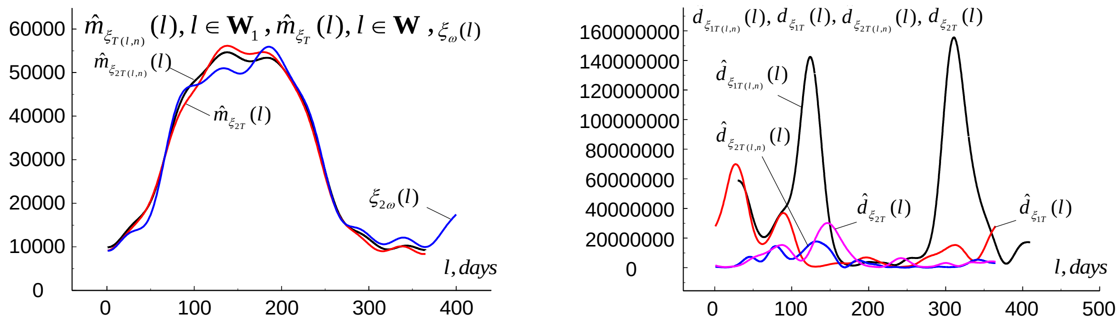
a) b)

Figure 7. Estimation of mathematical expectation and variance on the basis of taking into account the estimated function of the rhythm of the cyclic process of gas consumption (segmentation into cycles by depressions): a) estimation of mathematical expectation; b) estimation of variance



a) b)

Figure 8. Estimation of mathematical expectation and variance based on the period of the cyclic process of gas consumption for implementation (Fig. 4, b): a) estimation of mathematical expectation; b) estimation of variance



a) b)

Figure 9. Estimation of mathematical expectation and variance based on the period of the cyclic process of gas consumption for implementation (Fig. 4, b): a) estimation of mathematical expectation; b) estimation of variance

Discussion of the obtained results. While studying the implementation of the gas consumption process on the basis of mathematical model of the cyclic random process, statistical processing methods, which take into account the rhythm function are used. And while using the well-known mathematical model – stochastic-periodic random process, the processing is based on the period. The first approach to estimate the rhythm function uses the methods of segmentation of the studied implementation of the process of gas consumption – segmentation at the vertices and segmentation at the depressions. As a result, we obtained segment-cyclic structures and evaluated rhythm functions. Since the peaks of gas consumption process correspond to the winter season, and the depressions account for the use of gas in the summer season, the peaks reflect significant changes in gas consumption. Taking this into account this, it is not reasonable to segment the vertices. This confirms the fact that the obtained estimates of variances of gas consumption process (segmentation by vertices) have much higher values of variance $\hat{d}_{\xi_{1T(l,n)}}(l)$ compared to estimates of variances obtained on the basis of statistical methods based on the period $\hat{d}_{\xi_{1T}}(l)$. Taking into account the results of comparison of the obtained variance estimates (see Fig. 9, b) based on two mathematical models of stochastic-periodic process and cyclic random process, as well as taking into account two approaches to segmentation of the studied implementation by vertices and depressions, it follows that taking into account the rhythm function (mathematical model in the form of cyclic random process) based on segmentation by depressions, gives much less variance $\hat{d}_{\xi_{2T(l,n)}}(l)$ compared to other results, including on the basis of mathematical model in the form of stochastic-periodic random process $\hat{d}_{\xi_{2T}}(l)$.

Conclusions. New mathematical model in the form of additive mixture of three components: cyclic random process, trend component and stochastic residue is developed. Methods of statistical estimation of probabilistic characteristics of the gas consumption process based on the use of mathematical model in the form of cyclic random process are substantiated. Comparative analysis of the results of statistical processing of the gas consumption process showed that the new mathematical model in the form of cyclic random process gives less variance and therefore is more adequate than the known mathematical model in the form of stochastic-periodic random process, and statistical analysis methods significantly eliminate undesirable effect of statistical estimates «blurring», provided segmentation by depressions, not by peaks. It is not observed in case with the methods of processing of gas consumption process based on the period.

In further scientific researches it is planned to carry out the comparative analysis of the results of gas consumption process modeling on the basis of new mathematical model and the received statistical estimations.

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АДИТИВНА МАТЕМАТИЧНА МОДЕЛЬ ПРОЦЕСУ ГАЗОСПОЖИВАННЯ

Ярослав Литвиненко; Сергій Лупенко; Олег Назаревич; Григорій Шимчук; Володимир Готович

Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна

Резюме. *Розглянуто задачу побудови нової математичної моделі процесу газоспоживання. Нова математична модель подана у вигляді адитивної суміші трьох компонент: циклічний випадковий процес, трендова компонента та стохастичний залишок. Процес отримання трьох компонент здійснюється на основі застосування методу гусениці, при цьому отримуються десять компонент сингулярного розкладу. За такого підходу циклічна компонента формується із суми дев'яти компонент розкладу, які мають спільну ознаку – повторюване розгортання в часі. Трендова компонента нової математичної моделі – це друга компонента сингулярного розкладу, а стохастичний залишок формується на основі різниці значень досліджуваного процесу газоспоживання й суми циклічної та трендової компонент. Використано два підходи щодо стохастичного опрацювання циклічного процесу газоспоживання на основі відомої моделі стохастично-періодичного випадкового процесу та циклічного випадкового процесу як моделей циклічної компоненти. Застосування математичної моделі циклічної компоненти у вигляді циклічного випадкового процесу зі циклічною структурою дозволило отримати оцінку дисперсії на циклі процесу газоспоживання, за умови сегментації циклічної компоненти по впадинах, значно менше у порівнянні отриманої оцінки дисперсії для випадку застосування математичної моделі у вигляді стохастично-періодичного випадкового процесу. Це свідчить про значно більшу точність при опрацюванні процесу газоспоживання й дозволить використати отримані стохастичні оцінки під час моделювання процесу газоспоживання у подальших дослідженнях.*

Ключові слова: *циклічний процес, процес газоспоживання, статистичне опрацювання, сегментація, циклічний випадковий процес.*

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