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METHODS FOR ESTIMATING THE SHADOW ECONOMY OF UKRAINE UNDER CONDITIONS OF LIMITED DATA

In the face of modern challenges, particularly the limitations of statistical data, Ukraine encounters difficulties in accurately assessing the scale of the shadow economy. At the same time, reducing the shadow economy is a critical step for Ukraine in fulfilling its obligations to the European Union and integrating into the European community. This will promote sustainable development, attract investments, ensure social justice, and enhance the country's competitiveness on the international stage. The aim of the study is to conduct a comprehensive analysis of contemporary methods for assessing and forecasting the shadow economy, as well as to adapt these methods to the specific conditions of limited data in Ukraine. The research provides an analysis of modern methods for assessing the shadow economy and their adaptation to Ukraine's context of limited data. The study examines key classical approaches, such as the household expenditure method, the electricity consumption method, the monetary method, and the cash demand model, along with their limitations in the context of the pandemic, war, and economic instability. To address these challenges, the research proposes the use of modern tools, such as MIMIC models, Bayesian models, and transaction data analysis, which account for incomplete information and allow for the adaptation of shadow economy assessments to Ukraine's realities.

Keywords: *econometric modeling; statistical forecasting; modeling with incomplete data; shadow economy; methods adaptation.*

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МЕТОДИ ОЦІНКИ ТІНЬОВОЇ ЕКОНОМІКИ УКРАЇНИ В УМОВАХ ОБМЕЖЕНОСТІ ДАНИХ

В умовах сучасних викликів, зокрема обмеженості статистичних даних, Україна стикається з труднощами у точному оцінюванні масштабів тіньової економіки. Натомість зниження рівня тіньової економіки є важливим кроком для України на шляху до виконання зобов'язань перед Європейським Союзом та інтеграції в європейську спільноту. Це сприятиме сталому розвитку, залученню інвестицій, забезпеченню соціальної справедливості та підвищенню конкурентоспроможності країни на міжнародній арені. Мета дослідження полягає у проведенні комплексного аналізу сучасних методів оцінки та прогнозування тіньової економіки, а також адаптації цих методів до специфічних умов обмежених даних в Україні. У результаті дослідження надано аналіз сучасних методів оцінки тіньової економіки та їх адаптацію до умов обмежених даних в Україні. Розглянуто основні класичні підходи, такі як метод витрат домогосподарств, метод електроспоживання, монетарний метод та модель попиту на готівку, а також їх обмеження в умовах пандемії, війни та економічної нестабільності. З метою подолання цих викликів дослідження пропонує використання сучасних інструментів, таких як моделі MIMIC, байєсівські моделі та аналіз транзакційних даних, які дозволяють враховувати неповноту інформації та адаптувати оцінку тіньової економіки до реалій України.

Ключові слова: *економетричне моделювання; статистичне прогнозування; моделювання з неповними даними; тіньова економіка; адаптація методів.*

Formulation of the problem. In the current conditions, Ukraine faces challenges due to limited statistical data, making it difficult to accurately assess the shadow economy. A precise analysis requires a comprehensive approach that combines various methods and data sources to achieve the most accurate results. For Ukraine, which aspires to join the European Union, the issue of reducing the shadow economy is becoming a key aspect on the way to fulfilling its obligations and integrating into the European community. Reducing the shadow economy not only meets the requirements of the EU, but also has strategic importance for the development of Ukraine in the context of its economic, political and social goals. This will create conditions for sustainable development, attracting investment, ensuring social justice and increasing Ukraine's competitiveness in the international arena. Therefore, in the context of limited statistical data in Ukraine, an accurate assessment of the shadow economy requires a comprehensive approach, which includes the use of various methods to obtain the most accurate results. This will allow the state to improve the efficiency of economic management, increase transparency, reduce corruption and ensure social justice. Determining adequate methods for assessing the shadow economy is an important step towards the economic development of Ukraine now and ensuring its economic security in the future.

Analysis of recent research and publications. Modeling the shadow economy under conditions of limited data is extremely important for Ukraine in the current situation, as the war and the process of European integration create additional challenges for economic governance and require adaptation to new realities with limited resources and statistical capabilities. Many modern researchers focus on various approaches to modeling the shadow economy under conditions of limited data. R. Dell'Anno et al. (2023) used econometric modeling to analyze the shadow economy in France, Spain, and Greece, emphasizing the limitations of data due to differences in national statistical methods [1]. P. Dybka et al. (2022) propose combining the MIMIC model and cash demand analysis to estimate the shadow economy in countries undergoing economic transition, highlighting challenges caused by a lack of accurate data during post-crisis recovery periods [2]. P. Fève et al. (2023) utilized a DSGE model to study the impact of shadow banking and regulatory policies, taking into account the limited availability of data on informal financial flows [3]. C.J. Costa Junior and colleagues (2021) also employed a DSGE model, focusing on the shadow economy under limited statistical data in developing countries, particularly during periods of fiscal adjustment [4]. R. Remeikienė et al. (2018) use the MIMIC model to identify the factors of the shadow economy in the Eurozone, especially to combat the lack of official statistical data by utilizing alternative indicators [5]. B. Trebicka (2014) describes the use of the MIMIC model as a tool for assessing the shadow economy, demonstrating how this methodology helps operate under conditions of incomplete or inaccurate data [6]. A. Ekici and S. Önsel Ekici (2021) propose an approach using Bayesian networks to understand the complexity of the shadow economy, enabling probabilistic estimates when data are fragmented [7]. R. Van de Schoot et al. (2021) analyze the use of Bayesian methods for modeling under uncertainty, emphasizing their effectiveness for working with limited data, for example, in the field of the shadow economy [8]. P. Dybka et al. (2019) propose a hybrid approach to measuring the shadow economy, which combines cash demand analysis and the MIMIC model, reducing the impact of limited data [9]. D.V. Nguyen and M.T.H. Duong (2021) explore the relationship between the shadow economy, corruption, and economic growth in BRICS countries using econometric models that account for the limitations of available indicators [10]. All these studies demonstrate that modeling the shadow economy largely depends on the chosen approaches, which enable the adaptation of methodologies to challenges associated with data scarcity.

The aim of the study. The aim of this work is to provide a comprehensive analysis of contemporary methods for calculating and forecasting the shadow economy, and to adapt these

methods to the specific conditions of limited data in Ukraine, ensuring a more accurate assessment of the current state and future trends of the shadow economy.

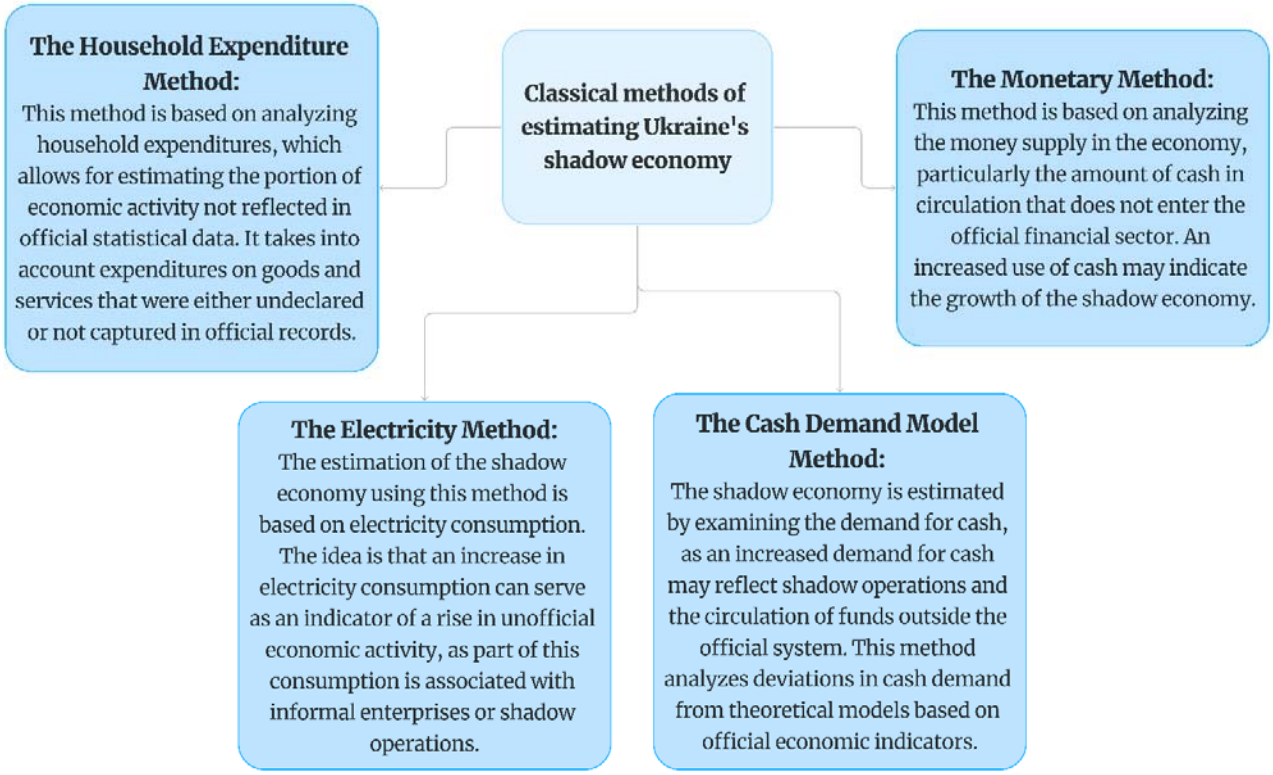
Research methods. The paper will apply several scientific methods to review existing methods, review and adaptation of the mathematical models to analyze Ukraine's shadow economy under limited data conditions. The literature review will provide information on various models (econometric, statistical, dynamic) used to study the shadow economy, particularly with incomplete data. Comparative analysis will assess the strengths, weaknesses, and applicability of each model to Ukraine's context, considering limited statistical data. The synthesis method will integrate results from different models and adapt them to Ukraine's economic context, adjusting parameters and using proxy data or methods for incomplete information. Additionally, the case study method will examine examples of model adaptation in similar countries, helping identify the most effective approaches for Ukraine's specific conditions and shadow economy characteristics.

Main material. The shadow economy is an integral part of the economic system in many countries, particularly in Ukraine, where a significant part of economic activity remains outside official monitoring. Its analysis is crucial for developing effective economic policies, combating tax evasion, and enhancing economic transparency. Various methods are employed to estimate the scale of the shadow economy, each with its own characteristics and limitations. The most commonly used approaches in Ukraine include the household expenditure method, the electricity method, the monetary method, and the cash demand model method. These methods allow for the analysis of different aspects of the shadow economy based on available statistical data and serve as essential tools for making informed decisions in economic policymaking.

The limitation of data for estimating the shadow economy in Ukraine is a significant issue, especially following the COVID-19 pandemic and the onset of the war, both of which have considerably complicated the collection and analysis of economic information. First and foremost, the pandemic, which began in 2020, severely disrupted the operations of economic institutions, businesses, and government agencies. Lockdowns, mobility restrictions, and the closure of many enterprises led to a portion of economic activity moving outside the official records. This increased the volume of shadow operations, as many businesses, particularly in the small and medium-sized sectors, were unable to operate legally and were forced to switch to informal schemes. As a result, data on household expenditures, energy consumption, and business turnover became incomplete, making it more difficult to use traditional methods for estimating the shadow economy. The war, which began in Ukraine in 2022, further worsened the data limitation situation. Infrastructure destruction, military actions in the eastern part of the country, and the occupation of certain territories led to many regions becoming inaccessible for the collection of official information. Statistical agencies and other state institutions responsible for monitoring the economic situation could no longer operate in their usual manner. Additionally, a large portion of businesses were forced to cease operations or move into the "shadow" due to the economic and social crisis brought about by the war. This led to significant distortions in data on economic activity, consumer spending, and energy consumption. Thus, both the pandemic and the war have resulted in serious difficulties in the collection, processing, and analysis of data, which are essential for assessing the level of the shadow economy. In the context of incomplete and fragmented data, traditional estimation methods become less effective, requiring an adaptation of analytical approaches and the use of new tools to more accurately reflect the economic reality.

In Ukraine, various methods are used to estimate the scale of the shadow economy, among which the most classical are: the Household Expenditure Method, the Electricity Method, the Monetary Method, and the Cash Demand Model Method. These methods provide a comprehensive assessment of the shadow economy in Ukraine, taking into account different aspects of economic

activity that are not captured by official statistics. Figure 1 presents these four classical methods in more detail.



Source: author's own research.

Fig. 1. **Classical methods of estimating Ukraine's shadow economy**

Thus, traditional methods of assessing the shadow economy, such as the household expenditure method, the monetary method, the electricity consumption method, and the cash demand model, are considered classic tools for analyzing hidden economic activity. These methods rely on statistical data processing, the analysis of behavioral patterns of the population and enterprises, and the identification of anomalies in economic functioning [11]. However, in the context of Ukraine in 2024, their effectiveness is significantly diminished due to several critical factors arising from the COVID-19 pandemic and the full-scale military invasion. The war and its associated consequences, such as the destruction of infrastructure, the forced displacement of millions of citizens, the economic crisis, and the instability of the banking system, significantly distort the economic indicators that underlie these methods. At the same time, the COVID-19 pandemic has changed traditional patterns of consumption and financial behavior, accelerated the digitalization of the economy, and reduced the availability of reliable statistical data. In the current conditions, classical methods face serious challenges: the unavailability of regional data, massive changes in expenditure structures, uneven access to energy resources and financial services, as well as changes in monetary flows due to wartime and volunteer initiatives. All these factors create significant obstacles to accurately measuring the shadow economy. Table 1 provides a detailed overview of the limitations and challenges faced by classical methods in assessing the shadow economy of Ukraine under the current conditions of war, the economic situation, and etc.

In sum, classical methods for assessing Ukraine's shadow economy have become outdated due to factors stemming from the war, the COVID-19 pandemic, and the economic crisis. Population displacement, inaccessible occupied territories, and infrastructure destruction undermine methods

based on household expenditures or electricity consumption. Changes in financial habits, digital payment growth, alternative energy use, and cash flows for military and volunteer needs distort traditional indicators. Inflation, economic instability, and low trust in banks further reduce the reliability of monetary models. These challenges necessitate developing new approaches tailored to current crisis conditions. Given the limitations of traditional methods, it is essential to explore alternative approaches for assessing Ukraine's shadow economy in the current context. The following three methods offer promising solutions that can better capture hidden economic activity in light of the ongoing war, the pandemic, and economic instability. The use of modern tools and new approaches makes it possible to better understand the scale of the shadow economy and its impact on the national economy. Further, new methods that can be applied for its assessment will be considered.

Table 1

Challenges in applying classical methods for estimating the shadow economy in conditions of limited data

No.	Method	Challenges in applying the method with limited data
1	Household expenditure method	Population displacement: Millions of Ukrainians have become internally displaced persons or have left the country, which affects the representativeness of household expenditure surveys. Many families incur expenses in other countries, while others are not accounted for in official statistics. Changes in expenditure structure: Most of the population changed their consumption habits during the war, prioritizing essential goods, while spending on services or durable goods significantly decreased. This distorts analysis models built on peacetime conditions. Inaccessibility of regional data: Many regions (especially occupied territories) are inaccessible for data collection, making it impossible to account for information from these areas. Lack of trust in surveys: Due to the stressful circumstances of the war and the pandemic, citizens may provide false information or refuse to participate in surveys altogether, which reduces the quality of the data. Lack of updated data: Statistical agencies are unable to keep up with rapid changes in population structure and the economy, meaning that most data is outdated or incomplete.
2	Monetary method	Military and volunteer operations: A large portion of cash circulates within charity, fundraising for the army, or volunteer initiatives. This creates the illusion of growth in the shadow sector, although this is not the case. Digitalization of payments: The pandemic accelerated the adoption of cashless transactions. This reduces the share of cash in circulation, making the monetary method less effective for detecting shadow transactions. Uneven access to banking services: The war has led to the closure of bank branches in many regions, shifting the demand for cash towards regional imbalances. Inflation and economic instability: Inflation and fluctuations in exchange rates affect the volume of cash in circulation, which may be perceived as a signal of the shadow economy, although it is a result of economic crises. Distortion of models: Classical economic models that account for stable cash behavior are not adapted to wartime conditions, where population behavior changes unpredictably.

End Table 1

No.	Method	Challenges in applying the method with limited data
3	Electricity Consumption Method	Destruction of infrastructure: Many power plants, power lines, and energy facilities have been damaged or destroyed, leading to uneven electricity consumption. Business exodus and shutdowns: A large number of businesses have either ceased operations or relocated abroad. This significantly reduces the correlation between economic activity and electricity consumption. Alternative energy sources: The use of generators, solar panels, and other energy sources has become widespread, especially after attacks on the energy system. This makes official electricity consumption data incomplete. Power supply disruptions: Due to regular power outages, consumption figures are uneven and do not reflect real economic activity. Lack of regional data: Data from occupied or frontline regions is unavailable, making the overall picture incomplete.
4	Cash Demand Model	Unpredictable behavior of the population: Due to military risks, many people keep cash at home as a security measure, which increases demand for cash, even if these funds are not used for shadow transactions. Military expenses: Increased demand for cash may be related to military needs rather than shadow transactions. Economic crisis: Hyperinflation and devaluation reduce trust in the banking system, leading to a rise in cash usage that is not linked to the shadow economy. Digital alternatives: The growing popularity of digital currencies (cryptocurrencies, online banking) reduces the relevance of the cash model for economic assessment. Inaccessibility of data: In many regions (especially occupied ones), the financial system is unstable or entirely absent, making it difficult to obtain accurate data on cash circulation.

Source: Author's own development [12, 13].

Table 2

Analysis of methods for assessing the shadow economy in Ukraine in conditions of limited and incomplete data

No.	Method	Description	How this approach is applicable to Ukraine's shadow economy
1	MIMIC model (Multiple Indicators Multiple Causes)	The MIMIC model allows for the calculation of the shadow economy level even in the absence of direct data, using indirect indicators and latent variables. In the context of Ukraine, where official statistics may be incomplete due to the war, this approach is very useful as it enables the processing of incomplete or partial data, establishing connections between various economic indicators.	Lack of complete statistics: Data that can be obtained through satellites, energy consumption analysis, cash transactions, or customs violations can be used as indicators for latent variables. Uncertainty and incomplete data: By using factor analysis, the MIMIC model can work even in the absence of complete and accurate data. This allows for the consideration of indirect indicators that, although not perfect, can still provide insights into the scale of the shadow economy.

End Table 2

No.	Method	Description	How this approach is applicable to Ukraine's shadow economy
			Multi-indicator approach: The model allows working with multiple data sources (e.g., energy consumption data or cash transactions), even if each of them has certain limitations or shortcomings.
2	Bayesian models using uncertainty scenarios	Bayesian models allow for the calculation of probabilities even in situations of high uncertainty, integrating expert assessments that can replace missing or incomplete data. This is particularly important in wartime conditions, when traditional sources of statistics may be disrupted or unavailable.	Uncertainty due to war: Due to the constant changing of conditions and instability (e.g., population displacement, infrastructure destruction), Bayesian models can account for these changes by updating probabilistic estimates in real-time. Expert assessments: Since official data may be incomplete, the model can use expert assumptions to estimate the size of the shadow economy, such as estimates of changes in energy consumption, shifts in currency flows, or assessments of corruption levels. Adaptability to new data: The collection of new, even partial, data can quickly impact posterior estimates, allowing for the adjustment of results based on new information.
3	Transactional data analysis and blockchain analytics	The analysis of transaction data and the use of blockchain analytics allow for the assessment of financial activity, including illegal transactions, even in the case of limited access to official banking or tax data. In situations where cash payments may be the primary method of settlement, this approach enables the tracking of anomalous transactions that may indicate the presence of the shadow economy.	Growth of digital payment systems: In Ukraine, the use of digital currencies and electronic payment systems is rapidly increasing, providing new data sources for analyzing the shadow economy, even when official data is limited. Inadequate official transaction data: Since some financial transactions may occur in the shadow economy (e.g., in the form of cryptocurrency transactions or unofficial money transfers), blockchain analytics helps identify anomalies in such financial flows. Use of cutting-edge technologies: The application of transaction analysis from cryptocurrencies and electronic payment systems allows for the identification of suspicious transaction patterns, even in conditions of limited or distorted data on official financial flows.

Source: author's own development [14–16].

Thus, the conditions of limited statistical data in Ukraine, particularly due to the war and instability, require the use of innovative approaches to assess the shadow economy. Methods that utilize indirect indicators, expert assessments, and the analysis of modern technologies such as satellite imagery, transaction data, or blockchain allow for the calculation of the shadow economy level even in the absence of complete or traditional data. These methods are adapted to the realities of Ukraine and can provide more accurate estimates in crisis situations and with limited information sources. For each of the methods for estimating the shadow economy, special formulas can be developed that take into account the incompleteness of statistical data. Here are possible formulas for each of the methods.

1. ***MIMIC Model (Multiple Indicators Multiple Causes).*** The MIMIC model assumes that the shadow economy is a latent variable that can be estimated using factor analysis. It is typically expressed as follows:

$$Y_t = \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \epsilon_t, \quad (1)$$

where Y_t – indicator of the shadow economy over time *t*; $X_1, X_2, \cdots, X_k$ – indicators that may be available (e.g. energy consumption, cash transactions, customs gaps); $\beta_1, \beta_2, \cdots, \beta_k$ – the impact coefficients of each indicator; ϵ_t – random error.

So in Ukraine, where data may be incomplete or partial, various data sources can be used, such as satellite-based night-time light intensity analysis, customs control changes, energy consumption, and so on. Since this data obviously may be incomplete, it is necessary to apply the maximum likelihood method or the Monte Carlo method to estimate parameters in the case of data incompleteness or low accuracy [17]. The maximum likelihood estimation (MLE) method estimates model parameters by maximizing the probability of observed data. For incomplete or inaccurate data, the following approaches can be used:

— Data imputation: Filling in missing values based on available information. MLE optimizes estimates considering these imputed data.

— Modification of the likelihood function: Using approximate likelihood functions that account for only available data.

— Estimation via the EM algorithm: An iterative process that estimates parameters by computing expected values for missing data and maximizing the likelihood.

The Monte Carlo method uses random samples to estimate complex functions or models, especially with incomplete or inaccurate data:

— Modeling uncertainty: Creating numerical simulations based on possible data variations (e.g., energy consumption, customs variables) to estimate likely scenarios.

— Simulations with data samples: Using random selection from available observations to estimate parameters, helping assess the scale of the shadow economy.

— Estimation with uncertainty: Accounting for data variability by creating simulated observation sets to estimate the probability of different levels of the shadow economy.

— Analysis with Bayesian methods: Combining with the Bayesian approach to estimate parameters considering probabilistic distributions.

Therefore, the application of maximum likelihood and Monte Carlo methods to assess the shadow economy in Ukraine allows processing incomplete or distorted data and contributes to more effective decision-making, helping to assess the scale of the shadow economy even in the absence of traditional statistics, which is critically important [18].

2. ***Bayesian models for estimating the shadow economy in Ukraine under conditions of uncertainty.*** The Bayesian approach effectively accounts for data uncertainty and incorporates

expert assumptions. The Bayesian approach allows us to estimate the probability of the shadow economy, taking into account uncertainty and new data. This approach combines available data with posterior distributions that are updated as new information becomes available. The formula for the posterior probability distribution of the shadow economy looks like this:

$$P(\theta|D) = \frac{P(D|\theta)P(\theta)}{P(D)}, \quad (2)$$

where θ – Model parameters describing the shadow economy (e.g., the size of the shadow economy); D – Available data (e.g. changes in energy consumption, cash transactions); $P(\theta|D)$ – The posterior distribution of the parameter θ (the estimate of the shadow economy level) based on the data D; $P(D|\theta)$ – The likelihood of the data given the parameter θ, plausibility of the data (if there is a probability that the data obtained correspond to a certain level of the shadow economy); $P(\theta)$ – The prior distribution of the parameter θ, incorporating expert assumptions or other prior information (distribution of parameters describing possible variants of the shadow economy before new data is obtained); $P(D)$ –The normalizing constant (the marginal probability of the data).

To achieve the most accurate estimation of Ukraine's shadow economy, expert assessments can be used for prior distributions, where instability and limited data lead to significant errors. For instance, data on changes in energy consumption or financial flow information can be incorporated into posterior estimates using posterior updating methods, such as Monte Carlo methods, to forecast changes in the shadow economy [19].

3. ***Transactional data analysis and blockchain analytics.*** This method involves using digital transaction data, such as transfers in payment systems, and analyzing data from blockchains to identify illegal operations that may be related to the shadow economy. The main goal is to detect anomalies in transactions that may indicate shady activity. The formula for identifying anomalous transactions might look like this:

$$T_a = \sum_{i=1}^{n} \delta(f(x_i, \theta) > \lambda), \quad (3)$$

where T_a – The number of anomalous transactions related to the shadow economy; x_i – Transaction i (includes attributes: amount, time, recipient, sender etc.); $f(x_i, \theta)$ – A function that evaluates the degree to which a transaction x_i deviates from the norm; the parameters θ set acceptable limits; λ – An abnormality threshold determined based on statistical or expert assessments; $\delta(\cdot)$ –Indicator function that takes the value 1 if the condition is met $f(x_i, \theta) > \lambda$; and 0 in the opposite case.

To identify anomalous transactions, the following methods could be applied:

— Clustering algorithms (e.g., k-means, DBSCAN) to group similar transactions.

— Graph analysis methods to explore connections between transaction participants, identifying nodes with suspicious activity.

— Machine learning techniques (e.g., SVM, Isolation Forest) to detect anomalies.

The application of anomaly detection algorithms spans several areas. In blockchain analytics, they help identify large cryptocurrency transactions that deviate from typical patterns, particularly through the use of graph algorithms to analyze nodes receiving substantial transfers from anonymous sources. In banking data analysis, average transaction amounts across different regions of Ukraine are compared, uncovering suspicious activity spikes in regions lacking an

economic basis for such flows. In the field of digital payments, transaction patterns are used to estimate the scale of informal activities in the e-commerce sector or during peer-to-peer transfers [20].

In sum, each of the methods has its own formula for estimating the shadow economy in conditions of incomplete data. The use of innovative approaches, such as MIMIC models, Bayesian models, and transactional data analysis, allows us to take into account not only official but also alternative sources of information, which can be useful in conditions of limited statistical data.

Conclusions. Classical methods for estimating the shadow economy, such as the household expenditure method, monetary method, electricity consumption method, and cash demand model, have limitations due to the lack of accurate data, especially during times of war or economic instability. The household expenditure method requires precise data on consumption patterns, but MIMIC models can work with incomplete data. The monetary method is challenging due to the lack of data on income and taxes, but Bayesian models can use probabilistic distributions and expert estimates. The electricity consumption method relies on data about energy usage, but blockchain analytics can detect shadow operations. The cash demand model depends on accurate data about currency circulation, but transaction data analysis can estimate the shadow economy through operations outside official channels. In contrast, the MIMIC model works with incomplete data by using multiple indicators such as energy consumption or customs gaps, which is especially important during war or economic instability. Bayesian models integrate various information sources, including expert estimates, and adjust evaluations based on new data, which is useful when accurate statistical data is lacking. Transaction data analysis, especially through blockchain, helps identify anomalous transactions that may indicate illegal flows, which are difficult to capture using classical methods based on official financial reports or tax data. So, MIMIC methods, Bayesian models, and transaction data analysis are more appropriate for estimating the shadow economy in Ukraine under conditions of limited data, as they allow working with diverse and incomplete information sources, including alternative data (such as energy consumption and cryptocurrency). These methods are more flexible and adaptive to realities like war, economic instability, and limited access to official statistics, making them more effective compared to classical methods that require more complete and precise data.

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