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Economic and mathematical modelling of sustainable extraction of natural resources

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SUMMARY

To determine the framework to ensure conditions for Ukrainian mining industry`s sustainable development, the methodological principles to determine the level of sustainability and to model the parameters and limits of sustainable development applying the case of coking coal and iron ore mining have been proposed. The method to measure the extractive sector`s level of sustainability, i.e. the sustainability index, which is determined on the basis of the linear and quadratic deviation of production volumes, has been proposed. The method to measure coking coal and iron ore mining level of sustainability has been developed using statistical indicators of relative and accumulated frequencies, which made it possible to obtain absolute indices of sustainability level in kind. It has been recommended to measure the extractive sector`s limit of sustainability finding the extremum of functions that describe the regression relationships between coke and ore production from the extracted raw materials, taking into account export-import flows and their use in metal production. The obtained modelling results provide an opportunity to forecast the optimal volumes of mining as a basis for sustainable development management of the Ukrainian extractive sector.

Introduction

Ukraine is one of the world leaders by the explored reserves of coal, iron, manganese, titanium and zirconium ores, as well as graphite, kaolin, potassium salts, sulfur, refractory clays, and facing stone. For instance, it has 7.5% of the world coal reserves, 15% of iron ore reserves. At present, Ukraine extracts significant amounts of hard coal (1.5% of the world production) and commercial iron ore (4.5%). Nowadays, the pace and scale of its own mineral resources base reproduction do not meet the country`s needs. The lack of funds reduced geologic exploration by 3-4 times. Therefore, since 1994, the explored reserves growth of most important minerals does not offset their extraction. Therefore, there is a need to form the system of rational minerals extraction. That is why, in our opinion, it is worth to model and forecast their production in the long run.

We consider, that system parameters of coking coal and iron ore production should be modelled in the context of the domestic metallurgy needs. The approach will, on the one hand, ensure domestic economy`s sustainable development, as 30% of its GDP and 27% of foreign exchange earnings are provided by the metallurgy. On the other hand, it will allow a more rational approach to the national resource use.

Method

In the analysis, general-scientific methods (analysis and synthesis, induction and deduction) and special methods of phenomena and processes analysis (abstraction, econometric and econometric-mathematical modelling) have been used.

Results

Total coal resources of Ukraine include 112.3 billion tons, 51.9 billion tons of explored reserve, including coking coal – 17.1 billion tons (30.5%) and anthracite – 7.6 billion tons (13.5%). Balance hard coal reserves are explored to the depths of 1200 – 1400 m, sometimes 1600 – 1700 m. Forecast and prospective hard coal resources are explored to the depths of 1800 – 2000 m. Today in coal production of Ukraine, 90 mines are subordinated to the Ministry of Energy and Coal Industry of Ukraine, but only 33 mines are located in the territory controlled by Ukraine. Moreover, of these mines, 24 operate (extracting about 21 thousand tons per day) and 2 operate in the mode of maintenance (in the drainage mode). Thus, the study shows a decrease in coal production in Ukraine in recent years. The needs for coal are met through import flows.

By the explored iron ore reserves, Ukraine is one of the world leaders. As of January 1st, 2020, the State Balance of Mineral Reserves of Ukraine takes into account 60 iron ore deposits, of which 25 are under development. Total balance reserves of iron ore are 18836.4 million tons, C2 – 7584.6 million tons; off-balanced – 4958.8 million tons. The development of 25 iron ore deposits by 12 mining companies continued during in 2019. Operational work was carried out at 7 mines and 13 quarries. In addition, ores that had previously been lost were mined too. In 2019, 167.9 thousand tons of previously lost saleable ores were mined in the field of the Ternivska mine. In 2019, 157.4 million tons of ore were mined in Ukraine (without impoverishment). Ore production compared to 2018 (152.6 million tons) rose by 4.8 million tons, which is 3.05%.

To optimize iron ore and coking coal production with simultaneous adjustment of import and export flows, it is necessary to determine the level and limits of sustainable development of such industries as metallurgy, coke and iron ore. As a measure of sustainability, let us use the stability factor (E,%), determined by the formula: $E = 100 – V$, where V is the coefficient of variation, which gives a relative estimate of variation and can be obtained by comparing the linear or standard deviation from the mean level phenomena, %. Production data in the industries were used for a period of 20 years. The formulas for the linear and quadratic mean deviation use the mean value determined by the theoretical trend equation as the mean value. The standard deviation is always greater than the linear deviation due to different methods of calculation. The linear deviation has the same units of measurement as the variant or the mean value, it gives an absolute measure of variation. The standard deviation is the deviation from the mean and it also has the same units as the variants or the mean. The calculation results are summarized in Table. 1. The iron ore industry has the highest stability factor – 84.41%, the stability factor for ferrous metallurgy and coke industry is approximately the same – 81.70% and 81.12%, respectively. Thus, this is fully corresponding to the economic situation regarding the dynamics of iron ore and coking coal mining in Ukraine.

The obtained results could be interpreted as follows. All industries have the cyclical nature of development during the study period, but the intensity of fluctuations in production volumes was not the same. Due to the lowest fluctuations in the iron ore industry`s growth rates, it has the highest stability factor.

Table 1 *Stability factor evaluation for the ferrous metallurgy and technologically related industries of Ukraine during 1991 – 2011s*

Industry	Mean linear deviation, million tons	Mean standard deviation, million tons	Linear coefficient of variation, %	Quadratic coefficient of variation, %	Stability factor (linear), %	Stability factor (quadratic), %
Ferrous metallurgy	15,88	20,85	18,30	24,03	81,70	75,97
Coke industry	4,15	4,93	18,88	22,41	81,12	77,59
Iron ore industry	9,66	13,40	15,59	21,63	84,41	78,37

To determine the absolute value of stability factor, we used statistical indicators of relative and cumulative frequency. These data in terms of mathematical statistics are a sample of 20 variants for each industry. A positive number that indicates how many times a variant has occurred in the data is called a frequency. Relative frequencies (the ratio of variant frequency to sample size) are often applied instead of frequencies. Relative frequencies illustrate how often over the past 20 years' certain production volumes have been identified in the analyzed industries. The results of the calculations are shown in Figure 1 - 2.

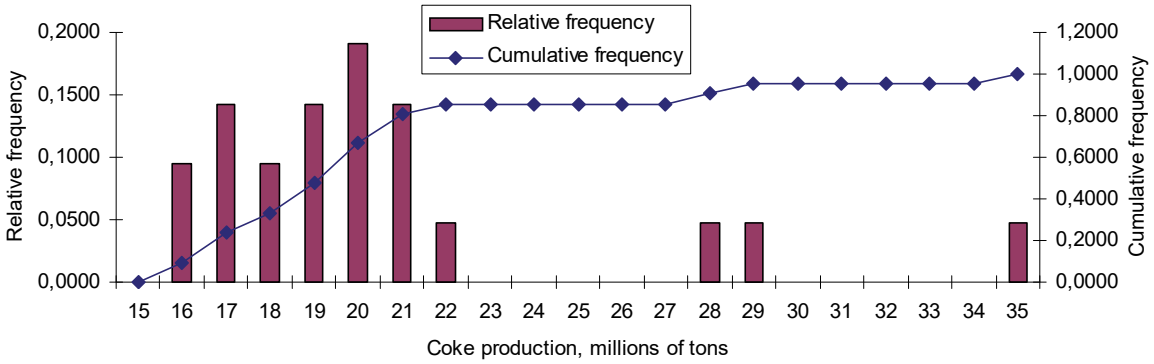

Figure 1 *Relative and cumulative frequency of coke production in Ukraine during 20 years*

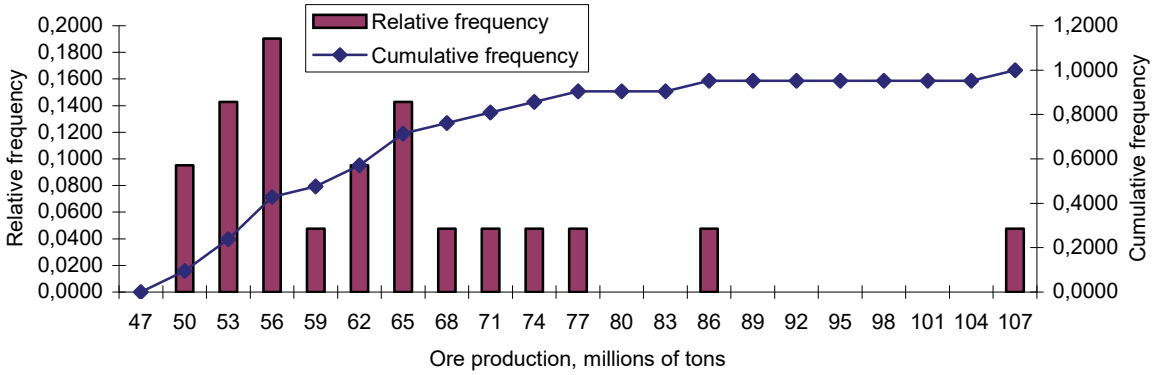

Figure 2 *Relative and cumulative frequency of ore production in Ukraine during 20 years*

We consider 93 millions of tons of ferrous metals production, 56 millions of tons of iron ore and 20 millions of tons of coke, respectively as optimal. These values are those production volumes that provide the required level of industry sustainability. Thus, the relative frequency of production is the absolute value of stability in kind. The obtained values can be considered as economic indicators of the stability factor.

An important task in forecasting the dynamics of coking coal and iron ore mining is to model the limits of changes in raw materials demand for the metallurgy, coke and iron ore industries. To do this, we have determined marginal values of the factor characteristic (extremum point). Its further growth will cause decline in metal production. It is determined by finding the extremum of functions that describe the regression relationships between coke and metal production, and ore and metal production. Let us draw in one figure the correlation between ore and coke production, and metal production (Figure 3).

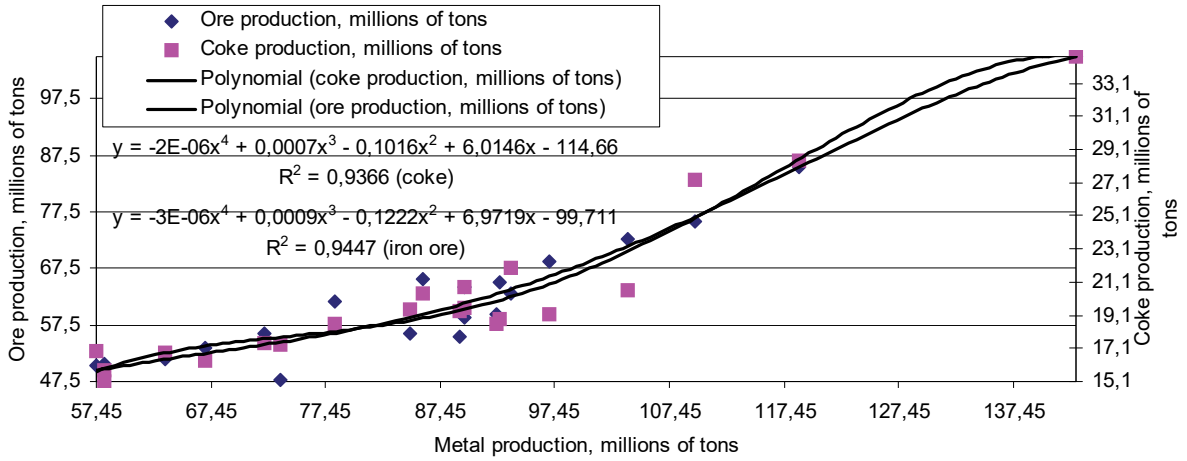

Figure 3 *Actual correlation of ore and coke production, and metal production in Ukraine*

Thus, the stability limits are 78 – 112 million tons for metal, 56 – 77 million tons for iron ore, and 18 – 25 million tons for coke. Based on the actual data on ore and coke production volume, we determine the equation of correlation between these values and ferrous metals production volume in Ukraine. We use the functions of MS Excel, i.e. a special LOGEST function (for the power law), which allows y in case when z is approximated variable, to depend on several independent variables – *x* and *y*. We obtain the following coefficients: a_2 = 1,0115, a_1 = 1,0135, a_0 = 31,4309. Standard errors of coefficients: 0,0055; 0.0160 and 0.1184, respectively; coefficient of determination is R^2 = 0,8023 and standard error is y = 0.1135; the F-test (Fisher's criterion) is 36.5178; the degrees of freedom are 18; regression sum of squares is 0.9413; the final sum of squares is 0.2320. That is, there is a sufficient degree of accuracy approximation (R^2 = 0,8023). Thus, the equation of correlation between ferrous metals production volumes (z) and coke (x) and ore (y) production volumes is: $z = 31{,}4309 \times 1{,}0135^x \times 1{,}0115^y$. Using these equations, we determine the theoretical ferrous metals production volumes in Ukraine and make the correlation between ore and coke production volumes and this value (Figure 4). The stability limits are 76 – 111 million tons for metal, 57 – 82 million tons for iron ore and 18 – 26 million tons for coke. Thus, the theoretical curve coincides with the curve built on the basis of actual statistics. Ukraine exports and imports not only metal, but also ore and coke, so we will determine the safety factor taking into account these flows. That is, we are evaluating the stability limits of metallurgy and its supporting industries, based on the needs of ferrous metallurgy in coking and iron ore. To do this, when making the graph, we use data on ore and coke volume for the metallurgical industry (equal to the production volume in the country minus exports plus imports). We get another dependence, which, in our opinion, allows a more accurate measurement of the national economy`s stability factor (Figure 5). Thus, the stability limits could be narrowed to 88 – 105 million tons for metal, 41 – 61 million tons for iron ore and 18 - 22 million tons for coke. The absolute optimums of production volumes obtained above, namely 93, 56 and 20 million tons, respectively, are within the stability limits of industries.

Research of problems of extractive branch is carried out by Kruglov, O., Menshov, O., Kuderavets, R., Chobotok, I., Kruglov, O., (Kruglov and Menshov, 2017; Menshov et al., 2014).

Conclusions. The results of coking coal and iron ore development modelling in Ukraine have proved that the relationship between trends and cyclical development of ferrous metallurgy, coke and iron ore industries have to be taken into account.

The method to measure sustainability of the extractive industry on the basis of stability factor has been proposed. It has been found out that the iron ore industry (84.41%) has the highest stability

factor, and the ferrous metallurgy and coke industry have lower values – 81.70% and 81.12%, respectively. This is explained by the fact that ore production during the study period gradually grew and had lower (within 35%) fluctuations compared to other industries. The ferrous metallurgy and coke industry had fluctuations of 50-70%.

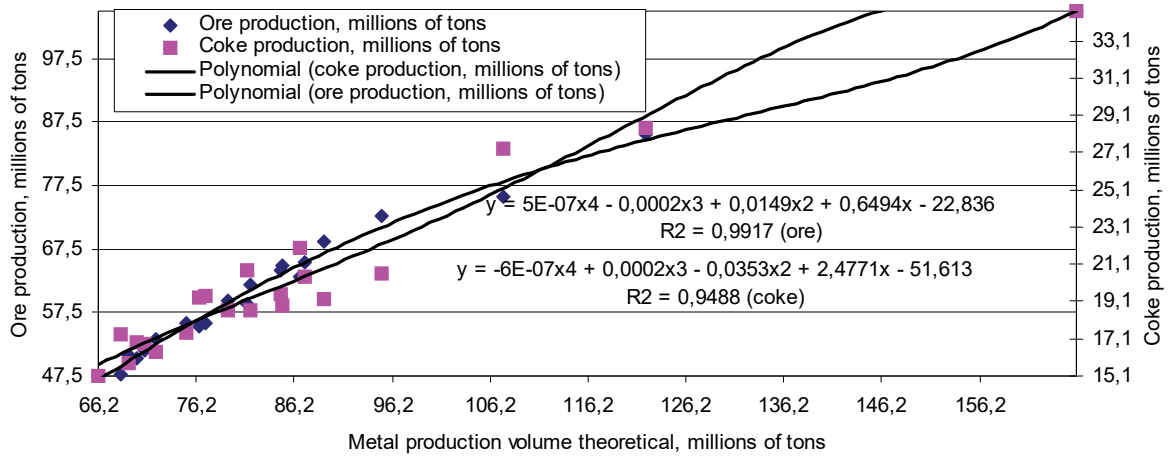

Figure 4 *Correlation between theoretical ore and coke production volumes, and metal production volumes in Ukraine*

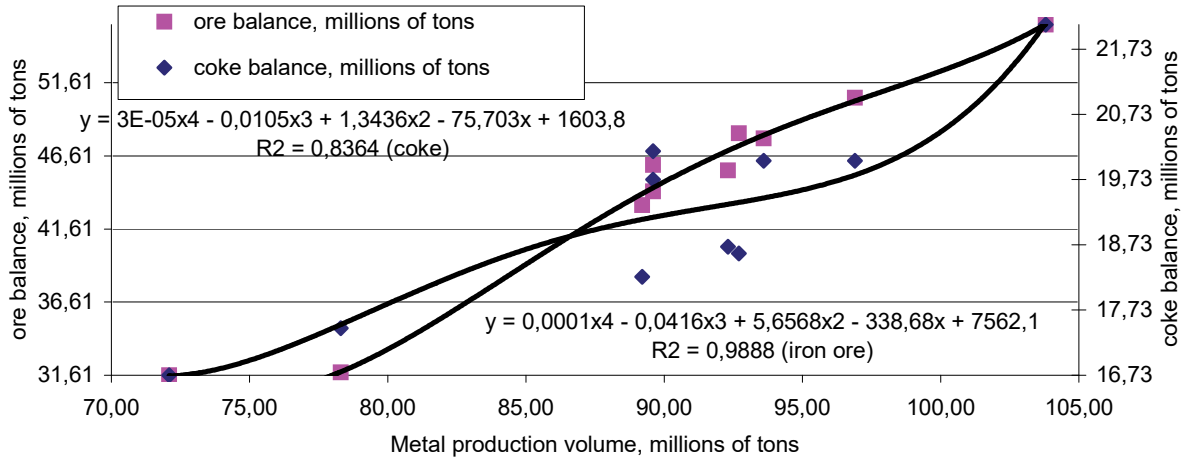

Figure 5 *Correlation between ore and coke balance, and metal production volumes in Ukraine*

The model has been built applying data on ferrous metallurgy, coke and iron ore industries` production volumes and statistical indicators of relative and cumulative frequency. This made it possible to obtain absolute indicators of the industries` stability factor in kind.

The stability limits of an economic system have been determined by finding the extremum of functions that describe the regression relationship between coke and ore production from the extracted raw materials, taking into account export-import flows and their use in metal production. A satisfactory correlation of the evaluation results of the absolute stability factor and its limits has been obtained.

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