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Assessing the clustering effect for extraction and processing of raw materials (using the example of the Kuzbass cluster "Complex processing of coal and industrial waste")

Evaluación del efecto de agrupamiento para la extracción y procesamiento de materias primas (utilizando el ejemplo del clúster de Kuzbass "Procesamiento complejo de carbón y desechos industriales")

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ABSTRACT

The paper considers a conceptual set of economic and mathematical problems, whose solution increases the efficiency of an innovative coal cluster that combines coal mining and processing industries. The effectiveness of the innovative clustering of coal mining is analyzed from three perspectives: for the regional economy, the cluster itself, and each of the cluster members. Thus, the paper studies the triune effect of the raw material cluster. In the course of the paper, the authors used the method of case study to consider the parameters of the raw material cluster “Complex Processing of Coal and Industrial Waste” in Kuzbass (Russia) to present a formalized description and calculate the general task of determining the triune effect of clustering coal mining and processing industries. The study results allow for more efficient development and application of technologies for complex and effective coal processing.

Keywords: coal mining industry, raw material cluster, economic and mathematical problems, synergetic effect, processing of man-made wastes.

RESUMEN

El artículo considera un conjunto conceptual de problemas económicos y matemáticos, cuya solución aumenta la eficiencia de un clúster de carbón innovador que combina la minería del carbón y las industrias de procesamiento. Se analiza la efectividad de la agrupación innovadora de la minería del carbón desde tres perspectivas: para la economía regional, para el propio clúster y para cada uno de los miembros del clúster. Así, el artículo estudia el efecto trino del clúster de materias primas. En el transcurso del artículo, los autores utilizaron el método de estudio de caso para considerar los parámetros del grupo de materias primas "Procesamiento complejo de carbón y desechos industriales" en Kuzbass (Rusia) para presentar una descripción formal y calcular la tarea general de determinar el efecto trino de agrupar las industrias de extracción y procesamiento del carbón. Los resultados del estudio permiten un desarrollo y una aplicación de tecnologías más eficientes para el procesamiento de carbón complejo y efectivo.

Palabras claves: industria minera del carbón, clúster de materias primas, problemas económicos y matemáticos, efecto sinérgico, procesamiento de desechos artificiales.

1. INTRODUCTION

Russia ranks second in the world in terms of coal reserves. According to various estimates, 17.6 to 18.2% of these mineral reserves are concentrated in Russia (over 157 billion tons) (Tolmachev et al., 2020). According to OPEC, oil reserves (at current production volumes) will last for 30-40 years, natural gas for 75-80 years, and coal for 400-500 years (Goncharenko et al., 2019). Consequently, coal will remain a strategic resource for Russia for a long time if compared to oil and gas (Salnikova and Grineva, 2021). However, the Ministry of Economic Development of the Russian Federation in the Forecast of socio-economic development for 2021 and the planned period of 2022-2023 (The forecast of social and economic development…, 2020) foresaw an 11.8% decrease in production from 2019 to 2023 (from 439.2 million to 387.4 million tons) due to a decrease in demand in European countries striving for a carbon-neutral economy. Decarbonization and carbon neutral development were proclaimed as goals in the Paris Agreement (Russia is a member state) which provides for the widespread reduction of CO_2 emissions. In 2019, the European Green Deal was adopted. Its objective is to completely stop greenhouse gas emissions and turn Europe into a climate-neutral continent by 2050 (A European Green Deal, 2021). China has also announced that it will achieve carbon neutrality by 2060. The implementation of this agreement and China's decision might reduce Russian hydrocarbon exports.

Russia has also proclaimed its transition to a carbon-neutral economy. The Strategy of Socio-Economic Development of the Russian Federation with a Low Level of Greenhouse Gas Emissions until 2050 (Decree of the Government of the Russian Federation of No. 3052-r, 2021) provides for a reduction in emissions compared to 1990. In further discussions of this document, it is planned to achieve carbon neutrality by 2060.

The decarbonization of the world economy is objectively one of the main trends in its development. In the foreseeable future, the further existence and development of the low-carbon coal industry should diversify its output through effective coal processing, in particular, through underground coal gasification.

According to I. Petrov (2022), a certain scientific and technological basis in this area has been laid by the USSR, i.e. studies in the field of obtaining synthetic liquid fuels and chemical products of hydrogenation processing and coal gasification, composite fuels, and products and materials for non-fuel purposes (Kuizheva et al., 2022). Currently, a working group on the development of effective coal processing and gasification, including underground, is functioning in the Ministry of Energy of the Russian Federation. The main task in regions with the developed coal industry (raw material regions) is to obtain the maximum effect from these processes (Goncharenko et al., 2019).

According to a group of authors headed by Yu. Friedman (Friedman et al., 2013), the current global crisis has shown that the only true strategy for the long-term development of resource regions is to get the maximum possible cash income from the extracted and processed raw materials. An important factor is that raw material industries act as drivers of the territory's innovative development since they are active consumers of innovations (Tatibekova et al., 2022; Malakhov et al., 2022). A. Savchenko (2015) claims that the most promising areas for the use of innovations are the technological support of the raw material industries and the effective processing of raw materials.

The localization of the coal industry in certain areas is a fundamental factor in the use of the cluster-based approach in organizing and managing the processes of coal mining and processing (Churin et al., 2019).

In our opinion, the maximum increase in the cost of a natural resource should be regarded as a clustering criterion: the maximum synergetic effect from integration for the business environment (Ukhina et al., 2022); the maximum total final financial result of the entire set of enterprises and organizations of cluster members (Kazaryan et al., 2022); the most effective use of the raw material reserve of the region where the cluster is located from the viewpoint of the development potential of this region's economy (Trusheva et al., 2022).

2. MATERIALS AND METHODS

Empirical context and case selection

When developing methodological support for determining the maximum positive effect from clustering the mining and processing potential of a raw materials region, it is necessary to use economic and mathematical optimization methods to quantify close relationships between the development of mining and processing industries from the standpoint of the chosen optimization criteria and development boundaries.

We adhere to the following formulation of the resource cluster as a form of integration of industries that extract and process natural resources. A resource cluster is a territorial integration of mining and processing enterprises that compete but also interact with each other and benefit from specific local raw materials, pursuing the goal of obtaining a systemic maximum effect (for the region's economy, the cluster itself, and its participants).

In the paper, we used the method of case study to consider the parameters of the raw material cluster "Integrated Processing of Coal and Industrial Waste" in Kuzbass (Russia). The development of this cluster begins in 2008 when the Concept of the Energy-Coal Cluster of Kuzbass was considered in the Strategy for the Socio-Economic Development of the Kemerovo Region until 2025. In 2011-2012, by the initiative of the regional administration, the first version of the Program for the Development of the Raw Material Cluster was developed. In 2014, the Program for the Development of the Pilot Innovative Territorial Cluster "Integrated Coal and Industrial Waste Processing" in the Kemerovo Region for 2014-2020 was adopted. In 2015, the cluster received a pilot status. In 2012, the Government of the Russian Federation included the Kuzbass cluster in the list of 25 innovation-territorial clusters of the Russian Federation. By order of the Government of the Kemerovo Region, a new Strategy for the Development of the Cluster "Integrated processing of coal and Industrial Waste" in the Kemerovo Region – Kuzbass until 2030 was approved in July 2021 (Order No. 359-r of the Government of the Kemerovo region, 2021). The strategic goal of the cluster development was to increase the competitiveness of the Kuzbass economy through the use of innovations and world experience in the field of integrated processing of coal and waste generated during its mining, enrichment, and combustion, as well as in the related areas.

Complexes for effective coal processing based on large coal deposits (Karakansky, Mencherepsky, Serafimovsky, Itatsky, and the Dalnie Gory mine) were called future promising residents. The basic directions in the cluster are as follows:

– The extraction and processing of coalbed gas (methane);

– The complex processing of coal and waste of its enrichment;

– The processing of ash, slag, and other industrial wastes.

The Kuzbass cluster is supposed to develop in the following three stages:

1) 2007-2013 – the preparatory stage preceding the creation of the cluster;

2) 2014-2020 – the formation of factor conditions for the cluster development;

3) 2021-2035 – the intensive creation of processing capacities and the development of sales markets.

Problem statement

The clustering process was divided into the following steps:

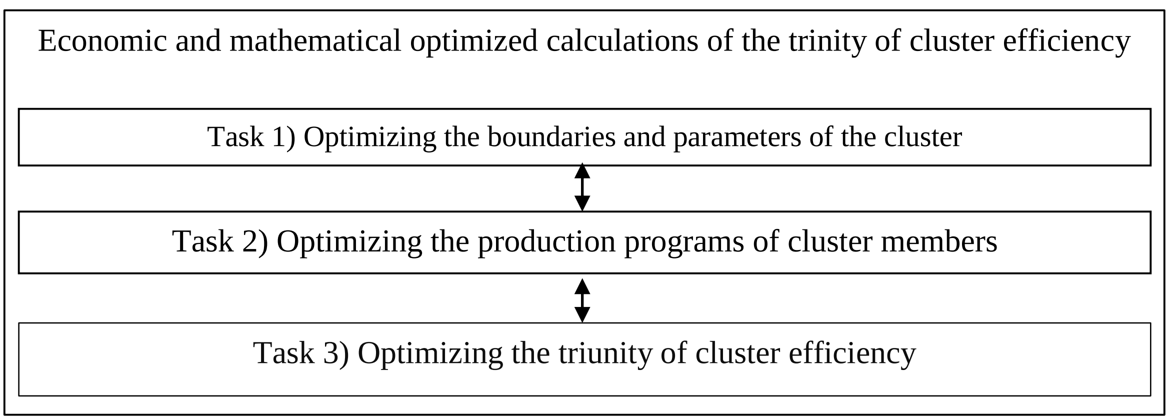
– The analysis of the possibilities and potential of clustering in terms of the socio-economic conditions of a particular industry or territory;

– The analysis and evaluation of the efficiency parameters of potential and real clusters;

– The analysis and forecasting of performance indicators of cluster members;

– The analysis and evaluation of the system (triune) efficiency of the cluster.

Schematically, the clustering process is shown in Figure 1.



Source: compiled by the authors
Figure 1. The conceptual logical diagram of optimization calculations

The triunity of the maximum effect predetermined the formulation and implementation of three main economic and mathematical problems (Mkrtchyan and Kritskii, 2016):

1) The task of optimizing the boundaries and general parameters of the cluster: the total parameters for the extraction and processing of coalbed gas (methane), the extraction and processing of coal and waste from its enrichment, the processing of ash, slag, and other industrial waste are determined under specified or approved (program) conditions and restrictions; the manifestations of possible economic and technological risks are assessed;

2) The task of optimizing the production program of enterprises participating in the cluster (to be solved for each enterprise): the effect on the business environment is determined;

3) The general task of optimizing the triune effect of the cluster: the effects for the region's economy, cluster, and each member enterprise are determined.

In our paper we present the formulation and implementation of the task 3). The theoretical economic formulation of this task is reduced to determining such operating costs for the production of a unit of each type of processed and manufactured products that would satisfy the given restrictions and the minimum total costs or the maximum total profit of the cluster would be achieved. From the theoretical viewpoint, the production of all types of x_{ijq} blocks can be variable and set values obtained from the task of optimizing the production program of enterprises within the cluster.

We introduced the following notation:

k is the number of coal types mined in the region;

i is the coal type index, $i = 1, \dots, k$;

f is the luster member enterprise index, $f = 1, \dots, F$;

l is the number of types of products processed from coal;

j is the index of the type of products processed from coal, $j = 1, \dots, l$;

x_{ijf} is the required volume of the *j* type of processed products from coal of the *i* type at the *f* enterprise;
s_{if} is the current costs of mining 1 ton of coal at the *f* enterprise;

s_{if}^{min} is the minimum required value of current costs for the extraction of 1 ton of coal at the *f* enterprise;

v_{ijf} is the desired specific operating costs for obtaining the *j* type of product from the *i* type of coal at the *f* enterprise.

Set indicators are as follows:

V is the forecasted value of operating costs for the production of all types of processed and manufactured products from all coal types;

O_i is the forecasted production of the *i* type of coal;

H_{ij} is the forecasted volume of the *j* type of processed products from the *i* type of coal;

r_{ijf} is the volume of the *i* coal type consumed in the production of a unit of the *j* type of products processed from coal at the *f* enterprise;

c_i is the selling price of a ton of the *i* coal;

a_i^{prod} is the capital intensity of production (per 1 ton) of the *i* type of coal;

A^{prod} is the forecasted value of investments in coal mining in the region;

p_{ij} is the selling price of a ton of *j* type of processed products from the *i* type of coal;

a_{ij}^{proc} is the capital intensity of production (per 1 ton) of the *j* type of processed products from the *i* type of coal;

A^{proc} is the forecasted value of investments in coal processing in the region;

w_{ijf} is specific labor costs (wage intensity) for the production (per 1 ton) of the *j* type of processed products from the *i* coal type at the *f* enterprise;

v_{ijf} is specific operating costs for the production (per 1 ton) of the *j* type of processed products from the *i* type of coal at the *f* enterprise;

d_f is the depreciation coefficient of fixed capital (investments) of coal processing at the *f* enterprise;

It is required to find such x_{ijf} and v_{ijf} under which the following conditions are satisfied:

$$\sum_{f=1}^{F}\sum_{j=1}^{L} r_{ijf} * x_{ijf} \leq O_i (i = 1, \dots, k; f = 1, \dots, F) \quad (1)$$

– The total volumes required for all types of products made from coal and for all enterprises should not exceed the forecast volumes of coal production of the *i* type;

$$0 \leq x_{ijf} \leq H_{ijf}\ (i = 1, \dots, k)\ (j = 1, \dots, l);\ (f = 1, \dots, F) \quad (2)$$

– The required volumes should not exceed the predicted volumes of the *j* type of processed products from the *i* type of coal;

$$I = \sum_{i=1}^{k} a_i^{prod} * O_i + \sum_{f=1}^{F}\sum_{i=1}^{k}\sum_{j=1}^{l} a_j^{proc} x_{ijf} \leq (A^{prod} + A^{proc}) \quad (3)$$

– Investments in the extraction of all coal types and the manufacturing of products made from all coal types should not exceed the forecast value of the total investment in the cluster (for example, from the Program);

$$\sum_{f}^{F}\sum_{i=1}^{K}\sum_{j=1}^{L} r_{ij} * x_{ijf} * v_{ijf} \leq V \quad (4)$$

– The total operating costs required for the manufacturing of all types of products should not exceed their specified value *V*.

Within constraints (1)-(4), the total volume of production and processing *S* (revenue) is maximized and chosen as an indicator of the internal efficiency of the coal chemical industry.

$$\sum_{f=1}^{F}\sum_{i=1}^{k}((O_{if} - \sum_{i=1}^{K}\sum_{j=1}^{L} r_{ij} * x_{jf}) * c_i - O_{if} * s_{if}) + \\ + \sum_{f=1}^{F}\sum_{j=1}^{L}\sum_{i=1}^{K}(x_{ijf} * p_{ij} - x_{ijf} v_{ijf}) = S \rightarrow \max \quad (5)$$

To be reflected in the cluster efficiency model for the region's economy, the following condition can be added which can act as a criterion:

$$AV = \sum_{f}^{F}\sum_{i}^{K}\sum_{j}^{L}(a_{ij}^{proc} x_{ij})d + \sum_{f}^{F}\sum_{i}^{K}\sum_{j}^{L} w_{ij} x_{ij} + (S - \sum_{f}^{F}\sum_{i}^{K}\sum_{j}^{L} v_{ij} x_{ij}) \rightarrow max \quad (6)$$

where the first component is depreciation, the second is labor costs, and the third is profit.

– The added value *(AV)* created in the processing component of the cluster is maximized, i.e. should take the maximum value.

To solve task 3), it is assumed that the desired reduction in the current operating costs (prime cost) in comparison with the solutions of task 2) will be a manifestation of a hypothetical synergistic effect of clustering.

Data analysis

Five cluster members were included in the task of optimizing the triune effect of the cluster (the first four are anchor, i.e. cluster-forming):

– The energy technology cluster based on the Karakansky-Zapadny surface mine (the extraction and utilization of methane, production of coke and chemical products, electricity, and construction materials);

– The energy technology complex for effective coal processing based on the Mencherepskoye coal mine (the production of chemical intermediates, coke-chemical products, and synthetic motor fuel from coal, the production of electricity and construction materials);

– The Serafimovsky energy technology complex with effective coal processing (the extraction and utilization of methane, production of chemical intermediates and products, environmentally friendly production of electricity, production of construction materials);

– The complex for the effective processing of brown coal based on the Itatskoye coal mine (the production of semi-coke and smokeless fuel briquettes, sorbents, and carbon materials);

– Other businesses.

According to the Cluster Development Program, the volume of integrated coal processing should have reached 200 million tons by 2020. This value was taken as the limit of the possible use of coal for processing. It was necessary to determine the maximum possible production of processed products: coke chemistry, gasification, hydrogenation, carbon materials, coal-water fuel, and processed man-made, ash, and slag waste. In addition to the total volume of coal processing, the gas produced during the preliminary degassing of coal seams was 4,000 million m^3, the volume of industrial waste use was 1,200 thousand tons, and the volume of ash and slag waste processed was 800 thousand tons. Experts consider possible limitations for the manufacturing of processed products. Other specific indicators for types of processed products were calculated in the same manner, including capital intensity and cost per ton. It is assumed that a synergetic effect should occur in the optimized unit cost of each type of product for each participating enterprise, an effect for the cluster as a whole should be present in the value of total profit, and an effect for the region's economy where the cluster operates should be expressed in the gross value added. Many studies (Bushueva, 2012; Khasanova, 2009) emphasize that the functioning of a group of interconnected industries in a given location reduces overall costs. The synergetic effect in a particular cluster depends on many factors, such as the number of cluster participants, the availability of resources, competition, and the mutual exchange of information and technological innovations.

Possible constraints include the values of revenue for each type of processed product obtained from the solution of task 2). As a result, it is necessary to determine an optimized structure of the total revenue of an enterprise within the cluster with a lower cost compared to the cost obtained in solving task 2).

3. RESULTS

The results of solving problem 3) for the anchor enterprises are presented in Table 1.

Table 1 – The results of solving task 3) if compared to solving task 2), million rubles in 2020 prices

		Results of solving task 3)	Results of solving task 2)
Karakansky coal energy subcluster	Revenue	13,636.47	13,636.47
	Prime cost	10,150.72	10,170.11
	Profit	3,485.76	3,466.36
Energy technology complex for effective coal processing based on the Mencherepskoye coal mine	Revenue	58,372.41	58,372.41
	Prime cost	53,051.36	54,170.71
	Profit	5,321.05	4,201.70
Serafimovsky energy technology complex with effective coal processing	Revenue	24,007.32	24,007.32
	Prime cost	19,486.46	19,551.88
	Profit	4,520.86	4,455.45
Ccomplex for the effective processing of brown coal based on the Itatskoye coal mine	Revenue	13,541.62	13,541.62
	Prime cost	7,557.13	7,656.72
	Profit	5,984.49	5,884.91
Total	Revenue	109,557.83	109,557.83
	Prime cost	90,245.67	91,549.42
	Profit	19,312.16	18,008.41
	Gross value added	68,947.28	

Source: calculated by the authors

4. DISCUSSION

Table 1 demonstrates that the total costs for each anchor enterprise decreased in relation to the solution of task 2). As a result, the total cluster profit increased (the effect for the cluster), and the gross value added was calculated (the effect for the region).

The results of solving task 3) for each type of coal processing product are indicative. Considering conventional calculations, the cost of production for traditional industries decreased and increased for processing industries (coal chemistry and hydrogenation) in three enterprises under consideration (except for Itatsky). Table 2 compares the solutions to task 2) and task 3) for one of the anchor participants in the resource-based cluster of Kuzbass, i.e. the Karakansky coal energy subcluster.

Table 2. The values of unit costs in solving tasks 2) and 3) for the Karakansky coal energy subcluster

	Methane, rubles/m^3	Oil fuel, rubles/ tones	Power generation, rubles/MWh	Semi-coke, rubles/tones	Coal chemistry products, rubles/tones	Construction materials, rubles/tones
The cost of solving task 3)	2,679.77	6,699.42	223.31	3,721.90	77,415.51	446.63
The cost of solving task 2)	3,000.00	6,000.00	250.00	3,800.00	100,000.00	450.00

Source: calculated by the authors

Target indicators were based on the initial expert information. To assess the systemic efficiency of the cluster, it is necessary to conduct a more thorough study of its technological and economic parameters.
Based on the analysis of the current situation in the coal and related industries, it can be assumed that the implementation of the Kuzbass Cluster Development Program will be accompanied by several problems:

– The financial costs required for the Program implementation will significantly exceed the stipulated values;

– The lack of coal processing technologies acceptable from economic and environmental standpoints;

– The market's unwillingness to accept coal-derived and carbon chemicals.

5. CONCLUSION

It is relevant to form the Kuzbass cluster as a strategic object and promote prospects for its further development. In world practice, more than five hundred products are manufactured from coal: gasoline, plastics, motor oils, lubricants, chemicals, etc. The development and application of technologies for complex coal processing have every reason to become a priority of world technological development in the foreseeable future.

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