Method of Analysis and Assessment of the Impact of Variable Demand from Hard Coal Consumers on the Degree of Utilization of Mine Production Capacities

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Abstract

The article presents the author's analysis of the utilization of the usable capacity of mines, which form part of a multi-plant mining enterprise, in conditions of variable demand for coal. The above analysis is based on Monte Carlo tools and is one of the elements developed by the author to rationalize production decisions for the management of a coal company.
The presented forecast analysis variants include:

- *assuming the expected value and dispersion according to retrospective data;*
- *the most probable forecast solution with a predictive formula;*
- *the application of correlated required changes.*

These results are based on the proposed forms of histograms, inferences about the size of adjusted production capacities, which are taken into account on the market, both in terms of quantity and quality of coal, and forecasting and the probability of applying these changes.

Keywords: *mining, production capacity, SIMPLEX algorithm, Monte Carlo method*

1. Introduction

A key element of the company's business strategy is to ensure full utilization of production capacity, because only then can the company achieve maximum profit. Any situation in which the degree of utilization of production capacity decreases results in an increase in the unit cost of production, maintaining empty fixed costs, and thus a deterioration of the financial result. This impact is more pronounced in a situation where the share of fixed costs in the unit cost of production increases. In other words, the greater the share of fixed costs in the cost structure, the more important the full utilization of the company's production capacity becomes.

In the conditions of coal mining, we are dealing with a situation of a significant share of fixed costs in the mine's cost structure (approx. 80%). Such a large share of fixed costs results from the specificity of the industry. The improvement of the financial condition of mining carried out as part of restructuring programs, in particular, consisted in reducing excess production capacity in relation to the variable demand for coal.

For this reason, it is important to conduct an analysis that allows for estimating the extent to which the production capacity of mines will be used, assuming real market situations that may occur. This is possible thanks to the method developed by the author, which uses Monte Carlo simulation [3, 4, 11, 12] to create a fairly large set of real scenarios of coal recipients' demand. The Monte Carlo method reflects with high probability real situations that may occur, and a large number of draws affects the certainty of the results. In this respect, the Monte Carlo method is superior to other methods used in similar analyses.

2. The essence of the proposed method

The basis for conducting the analysis of the impact of changes in demand on the degree of utilization of the production capacity of mines is a set of optimal solutions to the task of optimizing coal extraction and sales for a multi-plant mining enterprise. This set is created by repeatedly determining the optimal coal extraction and sales program for an assumed, random demand scenario, using the Monte Carlo method. The optimal solution is obtained using the SIMPLEX algorithm.

A random number generator was used to draw the vector of the demand size for the analyzed groups of recipients. The drawn demand vector is a set of subvectors of the right-hand sides of the condition regarding sales (2) of the model of quantitative and qualitative optimization of the hard coal mining structure [4, 5, 6]:

$$F=\sum_{j=1}^{p}\sum_{i=1}^{r_j}\sum_{k=1}^{m_{ij}}(c_{ijk}-kz_{ijk})\cdot x_{ijk}-\sum_{j=1}^{p}Ks_j\rightarrow \max \qquad (1)$$

$$\sum_{i=1}^{r_j}\sum_{j=1}^{p}\sum_{k=1}^{m_{ij}}x_{ijk_n}\le Z_k \quad \text{for all k,} \qquad (2)$$

$$\sum_{i=1}^{r_j}\sum_{n=1}^{m_{ij}}x_{ijk_n}\cdot b_{ijk_n}\le Qs_j \quad \text{for all j,} \qquad (3)$$

$$\sum_{i=1}^{r_j}\beta_{ij}=1 \quad \text{for all j,} \qquad (4)$$

$$x_{ijk}\ge 0\,, \qquad (5)$$

where:

c_{ijk} – price of the ij-type of coal accepted by the k demand group;

kz_{ijk} – unit variable cost of the i type of coal in the conditions of the j mine;

Tab. 1. Technical and economic coefficients for mines A, B and D. Source: Own preparation

Tab. 1. Wskaźniki techniczno-ekonomiczne kopalń A, B i D. Źródło: własne

Specification	Unit	Mine A	Mine B	Mine D
Average Extraction	ton/day	5,500	11,800	12,000
Max. Extraction	netto ton	1,600,000	2,700,000	4,600,000
Unit cost	PLN/t	136.90	159.02	115.87
Fixed cost	%	76.60	86.96	86.98

Tab. 2. Nominal prognosis value and dispersion σ_r for every group of consumers. Źródło: własne

Tab. 2. Nominalne wartości prognozy i dyspersji σ_r dla wszystkich grup odbiorców. Source: Own preparation

Name of consumer group	Nominal prognosis values (t)	Dispersion σ_r (t)
Export 8	300,857	95,728
Export 9	419,447	133,461
Indv. consumers 1	336,060	13,035
Indv. consumers 3	5,475,600	212,387
Indv. consumers 4	1,391,200	53,962
Dust kettles	2,385,300	92,521
Grates 2	265,940	10,315
Grates 3	1,095,000	42,472
Grates 4	567,619	22,017
Chamber grates 1	425,765	16,514

Tab. 3. The optimal plans of extraction and sales for A, B and D mines. Źródło: własne

Tab. 3. Optymalny plan wydobycia i sprzedaży dla kopalń A, B i D. Source: Own preparation

Mine A		
Offer: 1,600,000 t Sold: 438,968 t	Gross profits: -16,698,662 PLN Mine reserves: 734,180 t	
Consumers	**Coal assortment**	**Quantity (t)**
Indv. Consumers 4	nut coal	69,265
Indv. Consumers 4	pea coal	64,936
Indv. Consumers 3	fine coal I	304,767
Coal dump	fine coal II	401,738
Coal dump	slurry	25,109
Mine B		
Offer: 2,700,000 t Sold: 1,776,600 t	Gross profits: 62,938,398 PLN Mine reserves: 0 t	
Consumers	**Coal assortment**	**Quantity (t)**
Indv. consumers 4	nut coal	328,143
Export 8	nut coal	14,857
Indv. Consumers 1	nut coal	143,000
Indv. consumers 3	fine coal IA	237,000
Dust kettles	fine coal IA	330,000
Dust kettles	fine coal II	380,700
Export 9	fine coal II	342,900
Coal dump	fine coal II	923,400
Mine D		
Offer: 4,600,000 t Sold: 4,022,220 t	Gross profits: 371,140,074 PLN Mine reserves: 0 t	
Consumers	**Coal assortment**	**Quantity (t)**
Indv. consumers 4	cobble	101,200
Indv. consumers 4	nut coal	322,000
Indv. consumers 4	pea coal	414,000
Indv. consumers 3	fine coal I	2,120,600
Grates 4	fine coal II	567,620
Indv. consumers 3	fine coal IIA	496,800
Coal dump	fine coal II	7,380
Coal dump	fine coal II	570,400

Ks_j – total fixed cost of production in the conditions of the j mine;
x_{ijk} – net production of the ij-type of coal accepted by the kn demand group;
Z_k – demand of the k group of recipients;
Qs_j – total aggregate gross production of the j mine;
i – coal type index, i = 1, 2, ..., rj,
j – mine index; j = 1, 2, ..., p,
k_n – demand group index; k = 1, 2, ..., mij, where mij means the size of the kn set for ij type of coal;
b_{ij} – gross/net conversion factor;
β_{ij} – the share of the production of a given type of coal in the total gross production of the mine.

Each of the drawn demand vectors Z is a random variable with a normal distribution, with an expected value equal to the planned demand size. The standard error according to retrospective data, the most probable forecast error resulting from the prediction formulas and the correlated changes in demand were assumed as dispersion.

The study consists in obtaining new optimal coal extraction and sales programs taking into account different (random) coal recipients' demands. The results of the analysis are presented in the form of histograms of the degree of capacity utilization for individual mines. Based on these histograms, the probabilities of achieving the assumed levels of capacity utilization are determined.

Tab. 4. Nominal value and dispersion σ_{yprog} for every group of consumers. Source: Own preparation

Tab. 4. Nominalne wartości prognozy i dyspersji σ_{yprog} dla wszystkich grup odbiorców. Źródło: własne

Name of consumer group	Nominal prognosis values [t]	Dispersion σ_{yprog} [t]
Export 8	300,857	70,205.89
Export 9	419,447	116,913.60
Indv. consumers 1	336,060	10,565.02
Indv. consumers 3	5,475,600	140,552.80
Indv. consumers 4	1,391,200	35,710,60
Dust kettles	2,385,300	61,228.09
Grates 2	265,940	6,826.40
Grates 3	1,095,000	28,107.22
Grates 4	567,619	14,570.20
Chamber grates 1	425,765	10,928.80

Tab. 5. The compilation of the nominal forecast values P1 and P2, as well as the dispersions σ_{yprog} for each consumer group. Source: Own preparation

Tab. 5. Zestawienie nominalnych wartości prognozy P1 i P2 oraz dyspersji σ_{yprog} dla każdej grupy odbiorców. Źródło: własne

Name of consumer group	Nominal prognosis values P_1 (t)	Nominal prognosis values P_2 (t)	Dispersion σ_{yprog} (t)
Export 8	230,651.11	371,062.89	70,205.89
Export 9	302,533.40	536,360.60	116,913.60
Indv. consumers 1	325,494.98	346,625.02	10,565.02
Indv. consumers 3	5,335,046.20	5,616,151.80	140,552.80
Indv. consumers 4	1,355,489.40	1,426,910.60	35,710.60
Dust kettles	2,324,071.91	2,446,528.10	61,228.09
Grates 2	259,113.60	272,766.40	6,826.40
Grates 3	1,066,892.78	1,123,107.20	28,107.22
Grates 4	553,048.80	582,189.20	14,570.20
Chamber grates 1	414,836.20	436,693.80	10,928.80

Tab. 6. The compilation of nominal, minimum, maximum, and mean values of the predicted degree of production capacity utilization, as well as the probability of achieving these values for the nominal values P_1 and P_2, and dispersions σ_r and σ_{yprog}. Source: Own preparation

Tab. 6. Zestawienie wartości nominalnej, minimalnej, maksymalnej i średniej przewidywanego stopnia wykorzystania zdolności produkcyjnej oraz prawdopodobieństwa jego osiągnięcia dla wartości nominalnych P_1 i P_2 oraz dyspersji σ_r, σ_{yprog}. Źródło: własne

	The degree of production capacity rate [%]				Likelihood of attaining [-]			
							at least	
	Nominal value	*Minimum* value	*Maximum* value	*Average* value	Nominal value	*Minimum* value	*Maximum* value	*Average* value
Mine A								
σ_r	27.40	0	75.32	27.19	0.033	0.003	0.500	0.500
σ_{yprog}	27.40	0	81.28	27.35	0.082	0.003	0.520	0.520
P_1	27.40	0	45.26	3.86	0.623	0.003	0.319	0.012
P_2	27.40	15.75	91.73	56.25	0.002	0.002	0.520	0.990
Mine B								
σ_r	65.80	47.80	78.86	66.13	0.003	0.006	0.997	0.089
σ_{yprog}	65.80	65.80	90.67	66.71	0.057	0.003	1.000	0.114
P_1	65.80	65.80	78.47	66.85	0.043	0.009	1.000	0.135
P_2	65.80	65.80	92.44	66.79	0.070	0.003	1.000	0.100
Mine D								
σ_r	87.44	86.59	87.60	87.38	0.003	0.349	0.535	0.625
σ_{yprog}	87.44	85.01	87.60	87.29	0.003	0.423	0.557	0.638
P_1	87.44	84.86	87.60	87.07	0.003	0.099	0.170	0.648
P_2	87.44	86.91	87.60	87.53	0.003	0.710	0.866	0.784

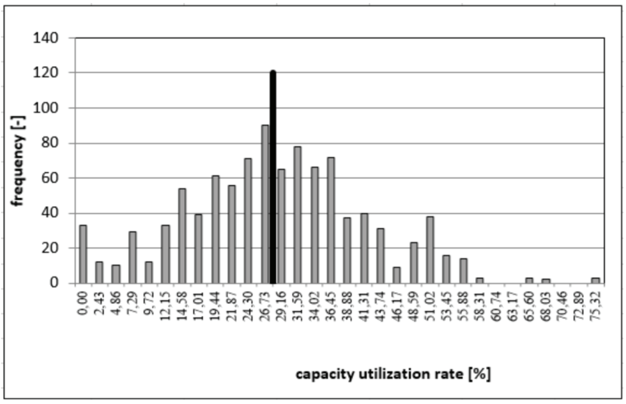

Fig. 1. Histogram showing frequencies of achieving given degree of operating leverage for mine A with dispersion σ_r. Source: Own preparation

Rys. 1. Histogram częstości uzyskiwanego stopnia wykorzystania zdolności produkcyjnej dla kopalni A przy dyspersji σ_r. Źródło: przygotowanie własne

3. Examples of calculations and evaluation of obtained results

Calculations were performed for selected mines A, B and D, which are part of the mining enterprise. Table 1 includes the production capacities of the analyzed mines A, B and D along with technical and economic indicators.

In the first stage of the analysis, the demand of individual customer groups was drawn according to the normal distribution with the expected (nominal) value equal to the planned demand (sales) value. For retrospective data, the best model for each customer group was selected using the regression method and on this basis the demand for the planned forecast year was forecasted. The adopted dispersion value (σ_r) is the standard error of estimating the regression function, which is a measure defining the average deviations of the actual values of the explained variable (demand of coal customers) from the theoretical values of this variable determined from the regression function. This is one of the parameters of the random component distribution, which allow conclusions to be drawn about the goodness of fit of the model to the empirical data [1, 2, 7, 8, 9, 10]. It is calculated using the formula:

$$\sigma_r^2 = \frac{\sum_{n=1}^{N}\left(y_n - y_{mod}\right)^2}{N-K} \tag{6}$$

where:
y_n – actual value of endogenous factor;
y_{mod} – model-based value of endogenous factor;
N – number of observations;
K – number of estimating parameters for model structure.

Table 2 presents the annual nominal values and dispersion of demand of individual customer groups. Table 3 presents the optimal extraction and sales plan for mines A, B and D.

The use of the Monte Carlo method to analyze the sensitivity of coal extraction and sales plans to changes in demand involves repeatedly determining the optimal coal extraction and sales program for mines with an assumed random demand scenario. The assumed number of 1,000 draws allows for obtaining a sufficient set of production tasks and corresponding financial results for individual mines, as well as calculating the degree of production capacity utilization. The obtained results are presented in Table 6 and illustrated in Figures 1-12. The vertical, black line shows the value of the degree of production capacity utilization resulting from the optimal plan, respectively for each of the mines.

The second stage is the analysis of the effects of random changes in demand according to the most probable forecast error. For this purpose, the error of demand forecasts for each of the recipients was estimated according to the formula [1, 2, 7, 8, 9, 10]:

$$\sigma_{yprog} = \sqrt{\sigma_r^2 + \sigma_{\hat{y}}^2} \tag{7}$$

by determining the forecast variance estimate:

$$\sigma_{\hat{y}}^2 = U \cdot U^T \cdot D^2 \tag{8}$$

also

$$U = [1 \quad x_{N+1}], \tag{9}$$

$$D^2 = \left[X^T \cdot X\right]^{-1} \cdot \sigma_r^2 \tag{10}$$

$$X = \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ 1 & x_3 \\ \dots & \dots \\ 1 & x_N \end{bmatrix}, \qquad X^T X = \begin{bmatrix} 1 & 1 & 1 & \dots & 1 \\ x_1 & x_2 & x_3 & \dots & x_N \end{bmatrix} \cdot \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ 1 & x_3 \\ \dots & \dots \\ 1 & x_N \end{bmatrix} = \begin{bmatrix} N & \sum x_N \\ \sum x_N & \sum x_N^2 \end{bmatrix} \tag{11}$$

where:
x_{N+2} – time, during which prognosis is prepared.

The nominal values and dispersions of customer demand used in this stage of the analysis are presented in Table 4. The obtained results are presented in Table 6 and illustrated in Figures 1-12.

In the third stage, the influence of correlated fluctuations in demand on the degree of utilization of the production capacity of mines was examined. For this purpose, the nominal value of the demand forecast for each recipient was reduced (P_1) in the first case, and increased (P_2) in the second case by the value of the model error (formula 7). The data obtained are presented in Table 5, while the results obtained are presented in Table 6 and illustrated in Figures 1-12.

As can be seen, mine A has too high production capacity in relation to the analyzed demand from customers. It uses only 27.4% of its production capacity. This is also the value most frequently occurring in the analyzed demand variants. The probability of such a situation occurring is about 0.5 for forecasts σ_r, σ_{yprog} and P1. Confirmation of the mismatch between the product structure and the requirements of customers is the possibility that it will not find customers for coal, with a probability of 0.033 (for σ_r), 0.082 (for σ_{yprog}) and 0.623 (for P_1) (Table 6, Figures 1-3). On the other hand, for forecast P_2, with a high probability of 0.99, the mine can use its capacity at a level of almost 92% (Figure 4).

Mine B also has too high production capacity in relation to the analyzed demand from customers. It uses only 65.8% of its production capacity. This is also the most common value in the analyzed demand variants. The probability of such a situation occurring in almost every variant is 1. The possibilities of using production capacity to a greater extent have a small chance of success, the probability is from 0.003-0.009. Achieving the average value of the degree of utilization of production capacity (higher in each case than the nominal value) is possible in 89-135 cases out of 1000 (Table 6, Figures 5-8).

On the other hand, mine D uses its production capacity at the level of 87.44% with the probability of such a situation occurring being 0.557 for σ_{yprog} (Table 6, Figure 10). The most probable situation is that the degree of utilization of production capacity in this mine may drop to 87.29%, as evidenced by the probability of 0.638. For forecast P_2, the production capacity can be used to a slightly higher extent, namely 87.53% with a probability of 0.784. In general, it should be stated that the mine is guaranteed to use the production capacity at the level from the optimal plan (Fig. 9-12).

4. Conclusion

The level of utilization of the production capacity of mines is directly influenced by the demand of current and potential coal recipients. Therefore, it is important to adapt the production structure of mines to the requirements of recipients not only in terms of quantity, but above all the quality of the coal offered. The results of the above analysis allow us to reveal

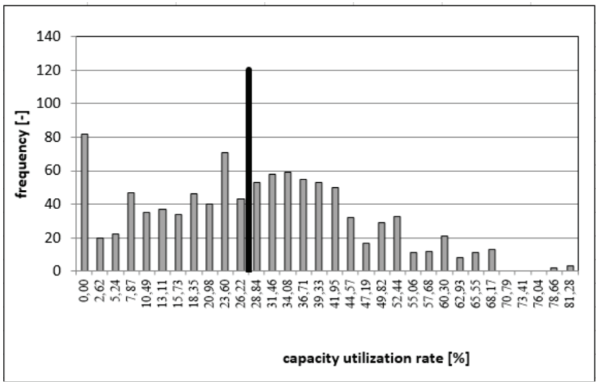

Fig. 2. Histogram showing frequencies of achieving given degree of operating leverage for mine A with dispersion σ_{yprog}. Source: Own preparation
Rys. 2. Histogram częstości uzyskiwanego stopnia wykorzystania zdolności produkcyjnej dla kopalni A przy dyspersji σ_{yprog}. Źródło: przygotowanie własne

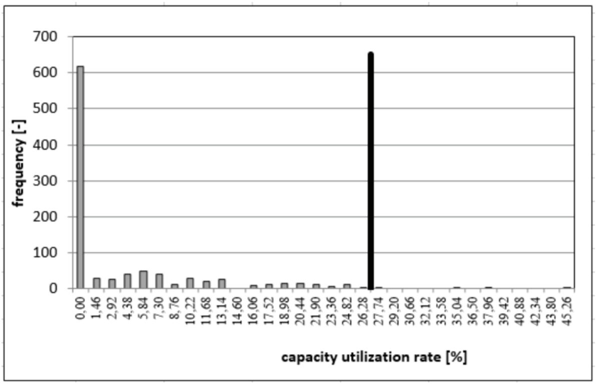

Fig. 3. Histogram of the frequency of obtained operational leverage degrees for mine A with the nominal value P_1 and dispersion σ_{yprog}. Source: Own preparation
Rys. 3. Histogram częstości uzyskiwanego stopnia wykorzystania zdolności produkcyjnej dla kopalni A przy wartości nominalnej P_1 i dyspersji σ_{yprog}. Źródło: własne

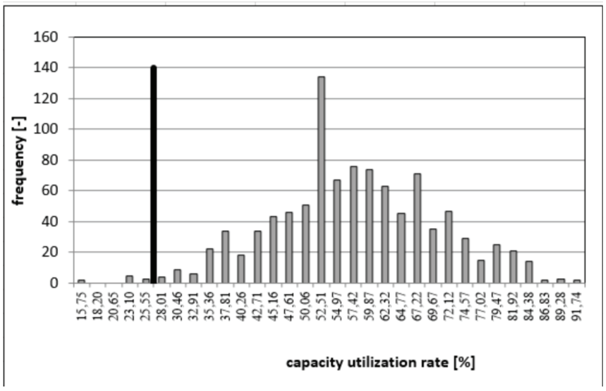

Fig. 4. Histogram of the frequency of obtained operational leverage degrees for mine A with the nominal value P_2 and dispersion σ_{yprog}. Source: Own preparation
Rys. 4. Histogram częstości uzyskiwanego stopnia wykorzystania zdolności produkcyjnej dla kopalni A przy wartości nominalnej P_2 i dyspersji σ_{yprog}. Źródło: własne

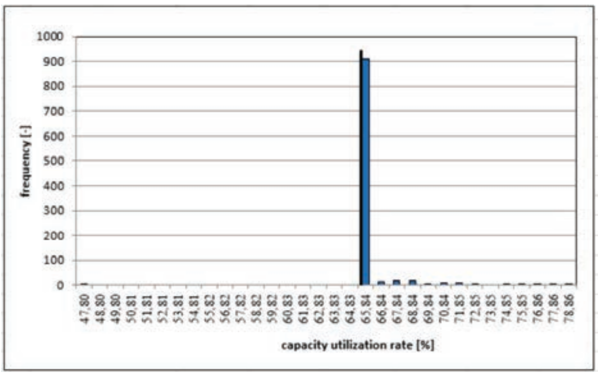

Fig. 5. Histogram showing frequencies of achieving given degree of operating leverage for mine B with dispersion σ_r . Source: Own preparation
Rys. 5. Histogram częstości uzyskiwanego stopnia wykorzystania zdolności produkcyjnej dla kopalni B przy dyspersji σ_r. Źródło: przygotowanie własne

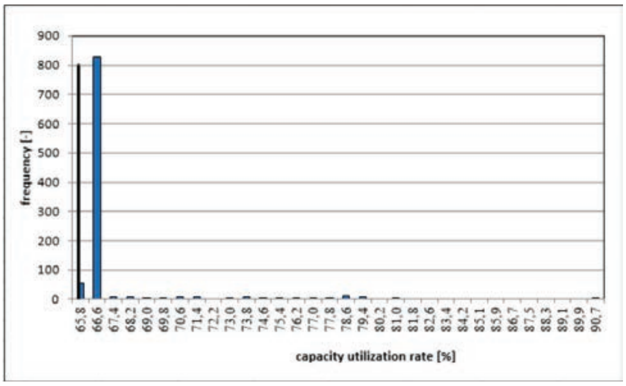

Fig. 6. Histogram showing frequencies of achieving given degree of operating leverage for mine B with dispersion σ_{yprog}. Source: Own preparation
Rys. 6. Histogram częstości uzyskiwanego stopnia wykorzystania zdolności produkcyjnej dla kopalni B przy dyspersji σ_{yprog}. Źródło: własne

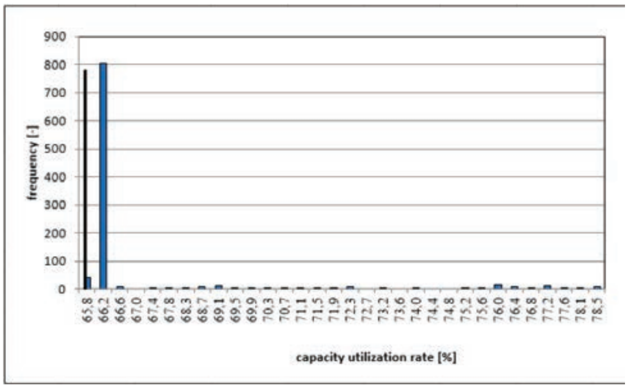

Fig. 7. Histogram of the frequency of obtained operational leverage degrees for mine B with the nominal value P_1 and dispersion σ_{yprog}. Source: Own preparation
Rys. 7. Histogram częstości uzyskiwanego stopnia wykorzystania zdolności produkcyjnej dla kopalni B przy wartości nominalnej P_1 i dyspersji σ_{yprog}. Źródło: własne

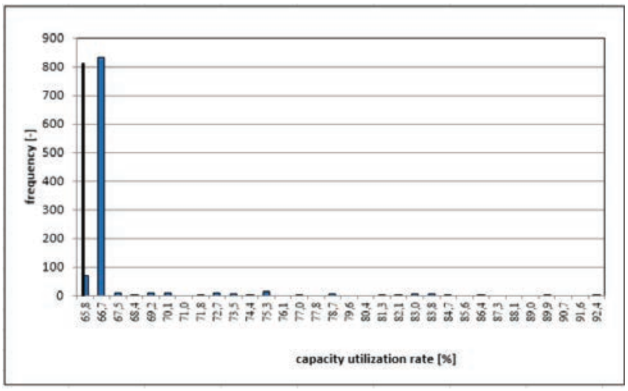

Fig. 8. Histogram of the frequency of obtained operational leverage degrees for mine B with the nominal value P_2 and dispersion σ_{yprog}. Source: Own preparation
Rys. 8. Histogram częstości uzyskiwanego stopnia wykorzystania zdolności produkcyjnej dla kopalni B przy wartości nominalnej P_2 i dyspersji σ_{yprog}. Źródło: własne

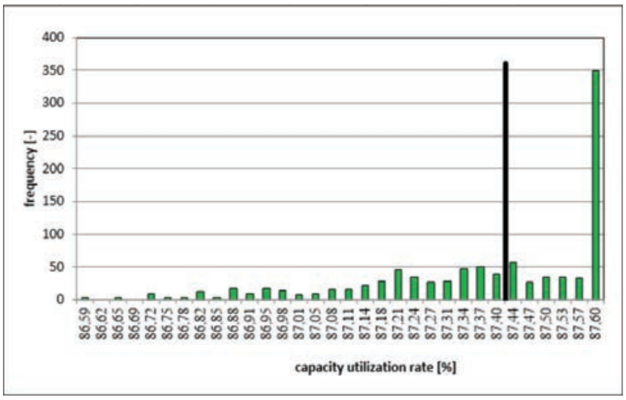

Fig. 9. Histogram showing frequencies of achieving given degree of operating leverage for mine D with dispersion σ_r. Source: Own preparation
Rys. 9. Histogram częstości uzyskiwanego stopnia wykorzystania zdolności produkcyjnej kopalni D przy dyspersji σ_r. Źródło: przygotowanie własne

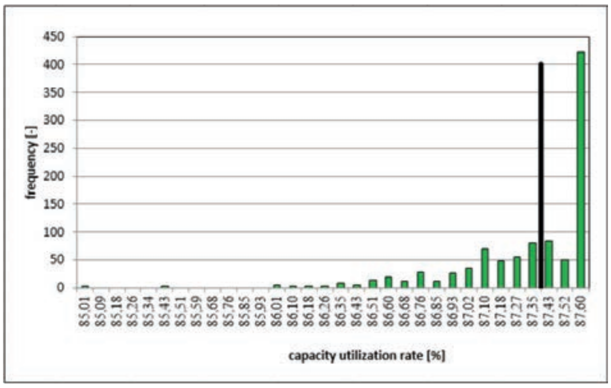

Fig. 10. Histogram showing frequencies of achieving given degree of operating leverage for mine D with dispersion σ_{yprog}. Source: Own preparation
Rys. 10. Histogram częstości uzyskiwanego stopnia wykorzystania zdolności produkcyjnej kopalni D przy dyspersji σ_{yprog}. Źródło: przygotowanie własne

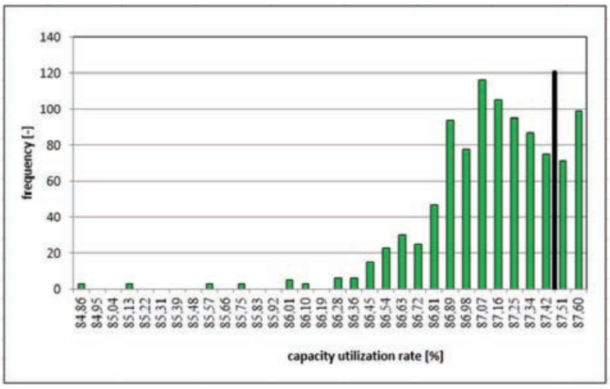

Fig. 11. Histogram of the frequency of obtained operational leverage degrees for mine D with the nominal value P_1 and dispersion σ_{yprog}. Source: Own preparation
Rys. 11. Histogram częstości uzyskiwanego stopnia wykorzystania zdolności produkcyjnej dla kopalni D przy wartości nominalnej P_1 i dyspersji σ_{yprog} . Źródło: własne

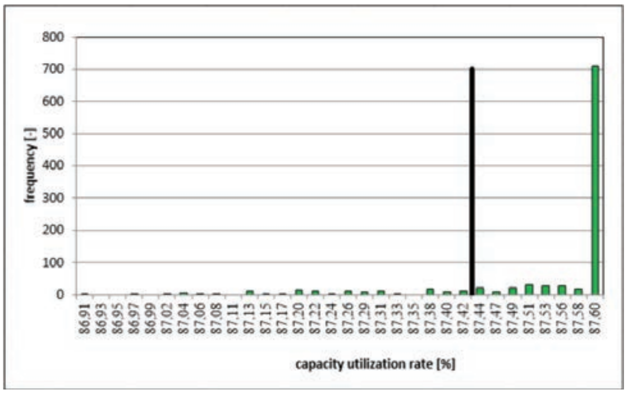

Fig. 12. Histogram of the frequency of obtained operational leverage degrees for mine D with the nominal value P_2 and dispersion σ_{yprog}. Source: Own preparation
Rys. 12. Histogram częstości uzyskiwanego stopnia wykorzystania zdolności produkcyjnej dla kopalni D przy wartości nominalnej P2 i dyspersji σ_{yprog}. Źródło: własne

the extent to which the production capacity of mines will be used, in what direction these changes will proceed and with what probability. This creates the opportunity for the management staff to undertake specific strategies regarding the further operation of mines (companies, companies, holdings). An example of this may be the need to take actions related to increasing production capacity through development investments - with the increase in demand from coal recipients exceeding the extraction capacity of mines. Although in the current situation related to the Green Deal, this variant is unlikely. However, with a decrease in demand, it may be necessary to limit extraction, liquidate part of the production capacity, and in some cases even to liquidate the mine.

The applied analysis method and the results obtained as a result may therefore be useful tools for supporting decisions both regarding investment and liquidation of unnecessary production capacity.

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Metoda analizy i oceny wpływu zmiennego zapotrzebowania odbiorców węgla kamiennego na stopień wykorzystania zdolności produkcyjnych kopalńch

W artykule zaprezentowano opracowaną przez autora metodę analizy stopnia wykorzystania zdolności produkcyjnych rzeczywistych kopalń, wchodzących w skład wielozakładowego przedsiębiorstwa górniczego, w warunkach zmiennego zapotrzebowania na węgiel. Analiza powyższa oparta jest na symulacji Monte Carlo i stanowi jeden z elementów opracowanej przez autora metody racjonalizacji decyzji produkcyjnych dla potrzeb zarządzania spółką węglową.
Przedstawione warianty analizy prognoz uwzględniają:

- *przyjęcie wartości oczekiwanej i dyspersji według danych retrospektywnych;*
- *przyjęcie najbardziej prawdopodobnego błędu prognozy wynikającego z formuł predykcyjnych;*
- *uwzględnienie skorelowanych zmian zapotrzebowania.*

Uzyskane wyniki, w oparciu o proponowaną metodę w postaci histogramów, pozwalają wnioskować o stopniu dopasowania zdolności produkcyjnej kopalń do wymagań rynkowych, zarówno pod względem ilości, jak i jakości węgla, oraz przewidywać kierunki i prawdopodobieństwo występowania tych zmian.

Słowa kluczowe: *górnictwo, zdolność produkcyjna, algorytm SIMPLEX, metoda Monte Carlo*