The Method for Assessing the Impact of Variable Coal Demand on the Efficiency of Mine Operations

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Abstract
The method presented in the article is based on Monte Carlo simulation and involves studying the impact of random demand fluctuations on the efficiency of mines and mine groups (companies). For random demand fluctuations, a normal distribution is assumed, and the analysis variants presented include:

- Adopting the mean and variance values based on retrospective data,
- Considering the most probable forecast error resulting from predictive formulas,
- Taking into account correlated changes in demand.

The results obtained are presented in the form of histograms of the degree of operational leverage. These histograms allow for predicting how the degree of operational leverage of mines will develop, as well as estimating the direction and probability of these changes. The developed and verified sensitivity analysis using real examples constitutes a useful element in rationalizing decision-making processes.

Keywords: sensitivity analysis, degree of operating leverage, the SIMPLEX algorithm, the Monte Carlo method

1. INTRODUCTION

Changes in the level of coal requirement have a significant effect on the financial situations of both individual mines and groups. Therefore, in market conditions it is essential to carry out multivariate analyses to assess the sensitivity of coal production and sales plans, as well as other economic and technical quantities on changes in requirements.

The present author’s research [5, 6, 7] on the options for sensitivity analysis of coal production and sales plans, the product structure, reserves, capacity and so on to changes in demand have revealed the significant suitability of the Monte Carlo method in the unbalanced Polish coal market [3, 4, 12, 14].

The sensitivity analysis using the Monte Carlo method presented in this paper covers research on the effect of random fluctuations in demand on the profit and the degree of operating leverage on the basis of a real coal mine.

2. THE ESSENCE OF OPERATING LEVERAGE

Leverage (in terms of finance) is used when changing the values of certain economic quantities causes more than proportionate change in other economic quantities.

Any increase (decrease) in gross receipts from sales will bring the company a more than proportionate increase (decrease) in gross profit on sales (percentage-wise) - assuming constancy in other factors which affect its level. This is called operating leverage. In order to determine what change in profit will be accompanied by a specific gain in sales, the degree of operating leverage (DOL) is calculated [13]:

\[ DOL = \frac{\%\Delta \text{EBIT}}{\%\Delta S} \]  

or

\[ DOL = \frac{S_o - K_{Zo}}{\frac{\text{EBIT}_o}{1 - t}} \]  

where:

- \(\%\Delta \text{EBIT}\) – Percentage increase in profit before interest and taxes,
- \(\%\Delta S\) – Percentage growth in net sales,
- \(S_o\) – The value of net sales as of the base, (PLN),
- \(K_{Zo}\) – The level of variable costs as of the base, (PLN),
- \(\text{EBIT}_o\) – The level of profit before interest and taxes as of the base, (PLN).

The operating leverage mechanism is a useful tool in the ongoing management of a company. With it, the rate of change in profit can be determined, for example: with an increase (decrease) sales, for example, of 10%, the profit made by the company will increase (decrease) by 10% × DOL. The degree of operating leverage (DOL) will depend on the profitability of sales and the cost structure taking into account their variability. Its size varies depending on the level of sales, which is the basis for the calculations. Hence, the operating leverage is used, inter alia, for predicting a company’s future economic performance [13].

3. CHARACTERISTICS OF THE PROPOSED METHOD

The basis for an analysis of profit sensitivity and the degree of operating leverage to changes in demand is the set of optimal solutions for optimising production and coal sales for the mining company. The Monte Carlo method is used for this. The set of optimal solutions for optimisation is created by repeated calculation of an optimal programme for the production and sale of coal with a given, random, demand scenario. The optimal solution, however, is obtained using the SIMPLEX algorithm.

The analysis is conducted for a set of 1 000 random demand sets. The demand vector drawn is the subvector of the right sides of the 4 optimisation model equation [7];
Objective function:
\[
\sum_{j=1}^{n} \sum_{i=1}^{r} \sum_{k} (c_{ijk} - k_{zijk}) \cdot x_{ijk} - \sum_{j=1}^{p} K_{sj} \rightarrow \max
\]

Sales restrictions:
\[
\sum_{j=1}^{n} \sum_{i=1}^{r} \sum_{k} x_{ijk} \leq Z_{k}, \quad \text{for all } k
\]

where:
- \(x_{ijk}\) – net amount of extracted coal of \(ij\) type accepted by consumers in group \(k\), (netto tone),
- \(c_{ijk}\) – price of \(ij\) type of coal,
- \(k_{zijk}\) – variable cost for mine \(j\),
- \(K_{sj}\) – fixed cost for mine \(j\),
- \(Z_{k}\) – consumer demand for group \(k\),
- \(i\) – index of coal type, \(i = 1, 2, 3, ..., r\),
- \(j\) – index of mine, \(j = 1, 2, 3, ..., p\),
- \(k\) – index of consumer groups, \(k = 1, 2, 3, ..., m_{ij}\),

where \(m_{ij}\) marks numerosity miscellany \(k_{n}\) for coal of \(ij\) type.

The remaining restrictions in the model relate to the structure of production and the capacity of individual mines [7]. The reality of the solutions obtained is assured by allowing the possibility of storing coal.

Each of the randomly selected demand elements is a random variable with normal distribution. The projected volume of demand is adopted as the expected value (nominal) equal to the planned demand (sales). For retrospective data, the best model for each group of consumers was fitted using regression analysis, and based on this, the forecasted demand for the planned forecast year was determined. The adopted dispersion value (\(\sigma_{r}\)) represents the standard error of estimation of the regression function, which is a measure indicating the average deviations of actual values of the dependent variable (coal demand of consumers) from the theoretical values of this variable calculated from the regression function. It is one of the parameters of the random component distribution that allows us to infer the goodness of fit of the model to the available empirical data. It is calculated using the formula [1, 2, 8, 9, 10, 11]:
\[
\sigma^{2} = \frac{\sum_{n=N-K}^{N} r_{n} \cdot \rho^{n}}{N-K},
\]

Table 2 compares the annual nominal values and dispersions in demand for individual groups of customers. Table 3, meanwhile, presents the optimal production and sales plan for „B” and „D” mines.

For various coal products, the following sales prices were chosen:
The variable unit cost was estimated at 40 PLN/t.

The use of the Monte Carlo method for sensitivity analysis of coal production and sales plans to changes in demand involves multiple iterations to determine the optimal production and sales program for mines under assumed random demand scenarios. The selected number of 1,000 draws enables an adequate set of production tasks and corresponding financial results for the various mines to be obtained, as well as the calculation of the degree of operating leverage.

The obtained results are presented in Table 6 and illustrated in Figures 3-10. The vertical black line represents the value of the operational leverage resulting from the optimal plan for each mine.

In the second stage, an analysis of the effects of random changes in demand was conducted based on the most probable forecast error. To estimate the forecast error of demand for each consumer, the following formula was used [1, 2, 8, 9, 10, 11]:

\[
\sigma^2_{\text{yprog}} = \frac{\sum_{n=1}^{N} (y_n - y_{\text{mod}})^2}{N - K},
\]

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

The nominal values and dispersions of consumer demand used in this stage of the analysis are presented in Table 4. The obtained results are shown in Table 6 and illustrated in Figures 3-10.

In the third stage, the impact of correlated fluctuations in demand on the operational leverage of individual mines was examined. To do this, the nominal value of the demand forecast for each consumer was decreased (P1) by the value of the model error in one case and increased (P2) by the value of the model error in another case (Formula 6). The data is...
Analyzing the presented histograms (Figures 3-10) of the achieved operational leverage degree for mines “B” and “D,” their distortion can be observed. This distortion results from the mismatch between the production structure of the analyzed mines and the demand from consumers, as confirmed in previous studies [1].

The nominal value of the operational leverage degree for mine “B” is 6.52 (represented by the black vertical line). This means that a decrease in sales, for example, by 10%, will result in a profit decrease of 65.2%, and vice versa. The probability of maintaining such a leverage degree is 0.80 and 0.90, respectively, for σ_r and σ_yprog (Figures 3 and 4). With a decrease in demand to the P_1 level, the probability of achieving the nominal leverage value will be approximately 50% (Figure 5), while in the case of an increase in consumer demand to the P_2 level, it will be only 13% (Figure 6). In each analyzed case, there is a higher probability of a favorable situation for the mine, namely a decrease in the degree to the mean value. For σ_y, the DOL will be 6.28 (89% chance), for σ_yprog the DOL will be 6.41 (92% chance), and for P_1 and P_2, respectively, the DOL will be 6.19 (70% chance) and 6.29 (90% chance). Other values of the leverage degree may occur, but with a very low probability ranging from 0.001 to 0.129 (Table 6).

For mine “D,” the probability of achieving the nominal level of the leverage degree (represented by the black vertical line) is almost equal to 1 in each analyzed case, corresponding to a level of 2.16 (Figures 7-10). There are only 3 chances out of 1000 for the value 2.27 to occur (for σ_r and P_1) (Figure 2, Table 4).

5. CONCLUSION

The magnitude of the demand from potential and existing customers has a decisive impact on the mine’s production volume, and thus the effectiveness of the company. The presented method of analysis provides a useful tool in assisting decision making, particularly in the area of reasonable volumes for production and sale of coal and also when conducting specific strategies regarding the mine’s (company’s) continued operation. It also provides the basis for action to presented in Table 5, and the ob-tained results are shown in Table 6 and illustrated in Figures 3-10.
Tab. 6. The compilation of nominal, minimum, maximum, and mean values of the predicted operational leverage, as well as the probability of achieving these values for the nominal values P1 and P2, and dispersions $\sigma_r$ and $\sigma_{yprog}$. Source: Own preparation

<table>
<thead>
<tr>
<th>Degree of operating leverage (%)</th>
<th>Likelihood of attaining (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal value</td>
<td>Minimum value</td>
</tr>
<tr>
<td>Mine $B$</td>
<td></td>
</tr>
<tr>
<td>$B$</td>
<td>6.52</td>
</tr>
<tr>
<td>$B_{nom}$</td>
<td>6.52</td>
</tr>
<tr>
<td>$P_1$</td>
<td>6.52</td>
</tr>
<tr>
<td>$P_{nom}$</td>
<td>6.52</td>
</tr>
<tr>
<td>$P_2$</td>
<td>2.164</td>
</tr>
<tr>
<td>$P_{nom}$</td>
<td>2.164</td>
</tr>
</tbody>
</table>

Fig. 3. Histogram showing frequencies of achieving given degree of operating leverage for mine “B” with dispersion $\sigma_r$. Source: Own preparation

Rys. 3. Histogram częstości uzyskiwanych stopni dźwigni operacyjnej dla kopalni „B” przy dyspersji $\sigma_r$. Źródło: przygotowanie własne

Fig. 4. Histogram showing frequencies of achieving given degree of operating leverage for mine “B” with dispersion $\sigma_{yprog}$. Source: Own preparation

Rys. 4. Histogram częstości uzyskiwanych stopni dźwigni operacyjnej dla kopalni „B” przy dyspersji $\sigma_{yprog}$. Źródło: przygotowanie własne

Fig. 5. Histogram of the frequency of obtained operational leverage degrees for mine “B” with the nominal value P1 and dispersion $\sigma_{yprog}$. Source: Own preparation

Rys. 5. Histogram częstości uzyskiwanych stopni dźwigni operacyjnej dla kopalni „B” przy wartości nominalnej P1 i dyspersji $\sigma_{yprog}$. Źródło: przygotowanie własne

Fig. 6. Histogram of the frequency of obtained operational leverage degrees for mine “B” with the nominal value P2 and dispersion $\sigma_{yprog}$. Source: Own preparation

Rys. 6. Histogram częstości uzyskiwanych stopni dźwigni operacyjnej dla kopalni „B” przy wartości nominalnej P2 i dyspersji $\sigma_{yprog}$. Źródło: przygotowanie własne
adapt the production structure, both in terms of quantity and quality, to customer requirements. This method of analysis is likely to reflect real situations that might occur. The results obtained for the multi-variant change in demand enable a direct indication of what values the volumes analysed can achieve (for example: profit or the degree of operating leverage), and with what probability.

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Zaprezentowana w artykule metoda oparta jest na symulacji Monte Carlo i obejmuje badanie wpływu wahań losowych zapotrzebowania na efektywność kopalni oraz ich grup (spółek). Dla losowych wahań zapotrzebowania przyjęto rozkład normalny, a przedstawione warianty analizy uwzględniają:

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

Uzyskane wyniki przedstawiono w postaci histogramów stopnia dźwigni operacyjnej. Pozwalają one przewidywać, jak będzie kształtował się stopień dźwigni operacyjnej kopalni, jak również umożliwia oszacować, w którym kierunku zmiany te będą postępować i z jakim prawdopodobieństwem. Opracowana i zweryfikowana na realnych przykładach analiza wrażliwości stanowi przydatny element racjonalizacji procesów decyzyjnych.

Słowa kluczowe: analiza wrażliwości, dźwignia operacyjna, algorytm SIMPLEX, metoda Monte Carlo