Comparison Of Forecasts For Average Methane Concentration At Longwalls Using Autoregressive And Cause-Effect Models Using Daily Mining As Descriptive, Based On Data From The "Krupiński" Mine

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ABSTRACT.: This paper describes forecasts for the average concentration of methane for a specific day regarded as a mining cycle. Such forecasts are helpful in taking short-term measures to prevent methane hazards. It presents a comparison of forecast results using the autoregressive and cause-effect models based on a daily coal output at the longwall as a descriptive variable.
In the autoregressive model, a descriptive variable was the average concentration of methane on the preceding day with the reference to the day of the forecast. Individual prognostic equations were performed for each day of the week.
In the cause-effect model with daily coal output at the longwall as a descriptive variable, linear equations were used as prognostic models, in which the number of descriptive variables varied between one and three. The variables included the predicted coal output at the longwall on the day of forecast, on the preceding day and two days earlier. If any of the mentioned variables was insignificant for calculating parameters of the prognostic equation, then parameters were estimated excluding such a variable.
Ex post forecasts based on both models were prepared for two longwalls. These forecasts differed in the processing method and the number of working days per week. Distributions of absolute and relative errors in forecasts for the average concentration of methane were compared for each longwall. Both forecasts were regarded as accurate and equivalent.
Introducing a one-day forecast of methane concentration into the mining sector can enhance work safety by applying short-term preventive measures.
KEY WORDS: autocorrelation, autoregression, concentration of methane, forecast for methane concentration, daily output, coal mines

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I. INTRODUCTION

Theoretical solutions for problems concerning methane hazard in mine pits should be based on a wide range of the most accurate possible measurements that are taken simultaneously at many points of the ventilation network (Dziurzyński et al., 1991, Dziurzyński et al., 2001). Such possibilities are provided by telemetric measurement systems.

There have been serious changes in the world and Polish underground mines within the last 25 years. Mines were equipped with telemetric systems for measuring chemical and physical parameters in the mine atmosphere (Cierpisz et al., 2007). These systems also have many other functions, such as:

- measuring concentrations of some gases present in the mine atmosphere (methane, carbon oxide, carbon dioxide etc.) and physical parameters (air velocity, atmospheric pressure, temperature),
- informing about locally measured parameter and alerting about locally exceeded threshold settings,
- turning off locally or centrally power supply to equipments and machines,
- transmitting measured results to the surface,
- visualising, registering and archiving measured data,
- generating alerts in the telemetric control room if allowable limit values are exceeded,

- signalling damage to some elements of the system.

Due to the risk of methane explosion, turning off electricity in case of exceeded limit values of methane is the most significant function of the telemetric system. This system prevents ignition or explosion of methane that can be caused by the work of machines or electronic equipment.

As we have better knowledge on the phenomenon of methane emission to pits, the fundamental function of this system is registering and archiving measured data.

According to Polish regulations on mining, the forecast for methane content at longwalls is required prior to their exploitation. Such forecasts are based mainly on methane volume of the exploited coal seam, methane content in coal seams and strata above and below the exploited seam, and methane content in rock strata of relatively high porosity, in which methane occurs in free (not adsorbed) state, e.g. in strata of sandstone and rudaceous rocks. The accuracy of discussed forecasts is limited because measurements are not performed in all strata due to economic and technical reasons. Forecasts are also very important for planning the fundamental preventive measures addressing methane risk at longwalls, such as methods of ventilating longwall areas, degasification or using auxiliary ventilation tools (e.g. Karacan 2008, 2009, Krause, Łukowicz 2009, Lunarzewski 1992).

However, mining practice indicated that preventive measures had to be changed many times and adjusted to current methane risk, different from the one predicted in the above forecasts.

The available data measured by telemetric systems can be analysed and processed outside this system, which provides a wide and varied range of their application, including short-term forecasts for methane concentration at the longwall area (Badura 2001a, 2001b, 2004, 2007, 2008, 2011, Bobrowski et al. 2007, Dziurzyński et al. 1991, Dziurzyński et al. 2002, Szywacz, Wasilewski 2003).

This paper describes how to prepare a one-day forecast for the average concentration of methane at the longwall outlet by means of two methods: the autoregressive model forecast and the cause-effect model forecast, in which outputs on the day of the forecast and on the preceding days are descriptive variables, and compares results of both types of forecasts.

Analysed forecasts can be used to plan and implement short-term measures to prevent methane hazards in hard coal mines (e.g. by reducing output, increasing air flow to the longwall, using auxiliary ventilation equipment).

II. APPLIED PROGNOSTIC MODELS

Using data on methane concentration measured by sensors operating in the continuous mode, Badura (2013) prepared seven autoregressive models on the basis of his own observations made for over 2300 days on nine longwalls in mines belonging to Jastrzębska Spółka Węglowa S.A. Models referred to individual days of a week. They can be expressed as:

$$S_i=a_0+a_1P_{i-1} \qquad (1)$$

where S_i means predicted concentration of methane on i-th day (current day), P_{i-1} is the average concentration of methane measured on the preceding day, a_0 and a_1 are parameters of the equation.

True average concentration of methane can be described with the following equation:

$$S_{irz}=S_i+r_i= a_0+a_1P_{i-1}+r_i \qquad (2)$$

where r_i is a random factor, known as a residual.

The average concentration of methane on the current day was calculated from continuous measurements of methane concentration taken from 6:00:00 a.m. on the current day to 5:59:59 a.m. on the following day, which corresponded to a working day.

Parameters of the model (1) are presented in Table 1.

Table 1.

Parameters of autoregressive prognostic models

Model No.	Day		Parameter	Parameter
	Analysed	**Previous**	**a_0**	**a_1**
1	Monday	Sunday	0.2536	0.7241
2	Tuesday	Monday	0.1256	0.9623
3	Wednesday	Tuesday	0.1027	0.9014
4	Thursday	Wednesday	0.0468	0.9405
5	Friday	Thursday	0.0458	0.9459
6	Saturday	Friday	0.0869	0.7213
7	Sunday	Saturday	0.0534	0.7667

The papers by Badura (2003 and 2004) and Badura et al. (2008) confirmed that the description of quantity of emitted methane or the average concentration of methane within 24 hours required coal output on the day of calculations (the current day) on the preceding day, and often from two days earlier. These papers also described that a linear function of many variables, in which quantities of output on the above days were independent variables, could be used for that purpose. Experience of H. Badura suggests that the output on all the listed days does not always affect methane concentration or content. Significance of the output on particular days was tested while estimating parameters of the prognostic model.
Taking into account the above, the following initial prognostic model was assumed:

$$S_i = a_0 + a_1 W_i + a_2 W_{i-1} + a_3 W_{i-2} \qquad (3)$$

where S_i is a predicted average concentration of methane, W_i, W_{i-1}, W_{i-2} mining on the current day, preceding day, and two days earlier, respectively, a_0, a_1, a_2, a_3 – parameters of the prognostic model. The true measured value of the average concentration of methane S_{rzi} is expressed with the following equation:

$$S_{rzi} = a_0 + a_1 W_i + a_2 W_{i-1} + a_3 W_{i-2} + \varepsilon_i \qquad (4)$$

where ε_i - a random factor (residual).

Taking into account the occurrence of autocorrelation in the time series of the average random factor, estimation of model parameters (3) with the ordinary method of least squares produced ineffective parameters. Consequently, predicted values of the average concentration of methane calculated with the prognostic model (3) differed from true values. Therefore, the Cochrane-Orcutt method was used to estimate parameters of the model (3) (Madalla 2006). The method was available in the GRETL software developed at Wake Forest University, North Carolina, USA (Cottrell 2007, Kufel 2011).

This paper presents forecasts based on autoregressive and cause-effects models which are one-day forecasts.

Autoregressive forecasting (1) can be performed starting from the second day of the longwall exploitation when parameters of prognostic models for individual days are known. Higher accuracy for determining parameters of the cause-effect forecast (3) requires a significantly greater number of measured values of the average concentration of methane. For the purpose of this paper, parameters of the first model were estimated on a set of 30 measured data of the average concentration of methane. Subsequent prognostic models were developed using the increasing number of measurements of the average concentration of methane, starting from the first measurement.

In the ex ante forecast using the cause-effect model (3), the output on the day of the forecast was a predicted variable, and not the known one. Because forecasts discussed in the paper were prepared ex post, the output on the day, for which the forecast was made, was assumed as its true quantity.
One model was used to prepare fourteen forecasts. And new parameters of the model were calculated to prepare other fourteen forecasts. The procedure was repeated until all measured data were applied.
There 264 measured data in total, whereas the number of forecasts based on the cause-effect model (3) was 227.
The comparison of forecast results discussed below, refers to 227 days, for which forecasts were prepared using both models.

III. NATURAL AND TECHNICAL CONDITIONS OF THE LONGWALL N-6 IN THE COAL SEAM 330/2

To compare the accuracy of autocorrelation and cause-effect forecasts, measured data of the average concentration of methane in the ventilation area of the longwall N-6 in the seam 330/2, the “Krupiński” mine were collected.

As the exploited longwall N-6 in the seam 330/2 in the “Krupiński” mine contained the seam located in changeable geological conditions, it also resulted in variable conditions of the methane level near the exploited longwall panel.

For example, in one of boreholes, directly over the seam, there were cracked dark-grey claystone with a thickness of 1.80 m, cracked light-grey sandstone with a thickness of 1.60, sandy grey claystone with a thickness of 9.8 m. Over those strata, there was the first stratum of coal and coal with clay, having a total thickness of 0.8 m. The total thickness of rock strata indicated that coal stratum was over the seam 330/2 within a distance of 13.20 m.

And in the second borehole, there were the following strata over the seam 330/2: claystone with a thickness of 0.30 m, sandy claystone and sandstone interbed with a thickness of 6.10 m, sandstone with a thickness of 2.20 m, and sandy claystone with a thickness of 5.70 m. A stratum of coal with a thickness of 1.0 m was deposited over the above strata, that is, within a distance of 13.0 m.

It implies that rock strata between the seam 330/2 and the unnamed coal stratum differed in mineralogical and petrographic composition and thickness.

Also, the seam 330/2 was divided into strata by parting of mine waste. The number and thickness of those strata differed depending on coordinates of the analysed geological profile. For example, the coal seam in one place had a thickness of 3.50 m, in which coal strata constituted 54%, and in another place the coal strata was 1.10 m thick and formed a single layer with a high content of claystone in the roof part.

There were some non-exploitable seams within a short distance from the seam 330/2. Mineral strata with a considerable content of coal were also found in the bed.

Distance from other exploitable seams over the seam 330/2 varied. And the nearest seam 329/1, 329/1-2, which had been previously exploited, was within a distance from 35 m to 75 m.

The predicted total methane concentration at the longwall N-6 was 30.14 m^3/min for the planned output at the level of 4000.00 Mg/day. According to the forecast, ca. 48.6% of total methane content would origin from overlaying rocks, 26.5% from the exploited seam, and 24.9% from strata below the seam 330/2.

The longwall G-6 had the following geometric parameters:

- length - ca. 225 m,
- panel length - ca.1100 m,
- height from 2.80 to 2.96 m.

The exploited initial part of the longwall N-6 was under the seam where no exploitation works were performed. However, at the further panel of the longwall, the exploitation area was partially mined. Therefore, progress in exploitation resulted in a longer section of the wall under the depleted part of the seam 329/1, 329/1-2. Published results of measured concentration of methane covered the period of 256 days.

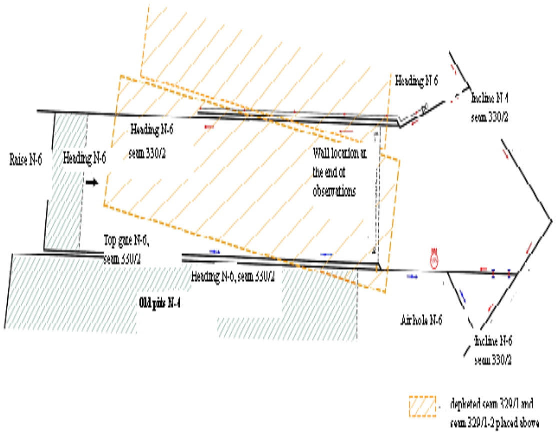

Fig. 1. Scheme of pits at the longwall N-6 in the seam 330/2 in the "Krupiński" mine

1. Description of measured data and forecasts for the average concentration of methane

Measured data at the longwall N-6 in the seam 330/2 covered 258 days. The average concentration of methane was calculated on the basis of data measured within the period from 6:00:00 am on the current day to 5:59:59 the next day. Table 1 presents basic parameters characteristic for the set of the average concentration values of methane.

Table 1. Statistical data for the set of average values of methane concentration at the N-6 longwall outlet

Number of days	Average	Median	3rd Quartile	9th Decile	Minimum value	Maximum value	Total	Coefficient of autocorrelation
258	0.67%	0.63%	0.87%	1.03%	0.19%	1.23%	173.31%	0.92

Fig. 2 illustrates a linear plot of the average concentration of methane at the N-6 longwall outlet in the seam 330/2. Due to many data and readability, the linear plot was used instead of the bar chart.

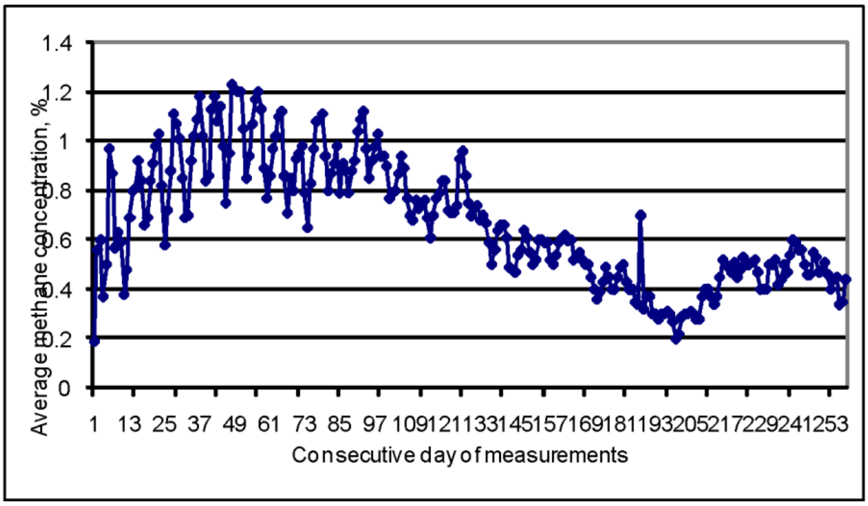

Fig. 2. Average concentration of methane at the outlet of the longwall N-6

In the initial phase of mining, there were clear variations in methane concentration on a weekly basis. They were caused by Saturdays and Sundays, on which days no exploitation was performed. Starting from the approach under the mined out part of the seam 329/1, 329/1-2, methane concentration was decreasing and weekly variations were also lower.

Statistical data typical for the set of measured data of the average concentration of methane and sets of methane concentration predicted with the autoregressive model (Forecast 1) and the cause-effect model (Forecast 2) are shown in Table 2. The cause-effect forecast covered 227 days, and the measured data and results of the autoregressive forecast referred to the same time period.

Table 2.
Statistical parameters of the average concentration of methane

	Average	Median	3rd Quartile	9th Decile	Minimum value	Maximum value	Total
Measurements	0.66	0.60	0.86	1.03	0.20	1.23	150.39
Forecast 1	0.67	0.63	0.84	0.98	0.26	1.21	151.12
Forecast 2	0.67	0.64	0.85	1.03	0.21	1.23	152.23

Data from Table 2 indicate that differences between measurements and forecasts were minor. The same conclusion can be drawn from plots of measured and predicted values as illustrated in Figs. 3 and 4.

As the number of measured and forecast points in Figs. 3 and 4 is considerable (227 points), differences between measured and predicted data cannot be estimated. Absolute and relative errors of forecasts were calculated for better analysis of conformity between measured and predicted values of the average concentration of methane. Then, they were used to evaluate the conformity between forecasts and measurements, and to compare these forecasts.

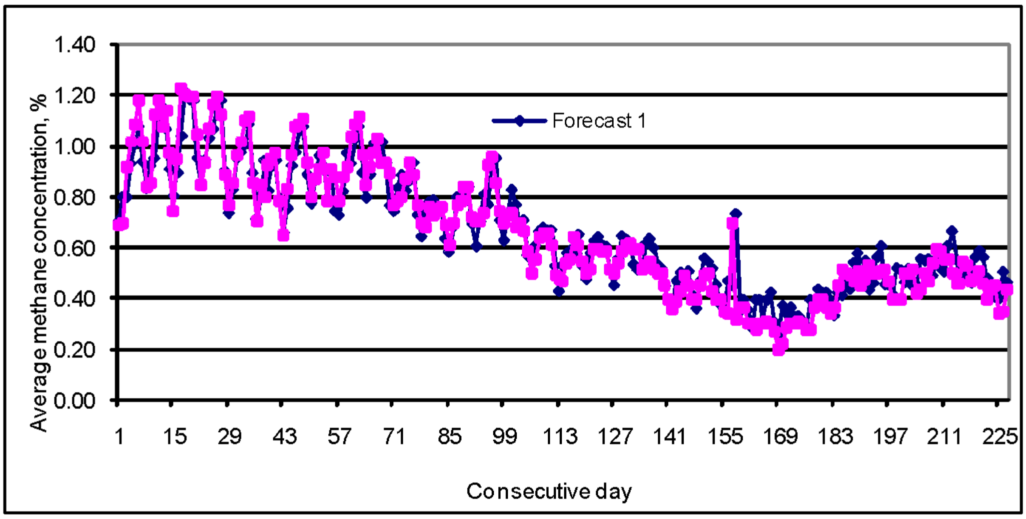

Fig. 3. Plot of values of the average concentration of methane obtained from measurements and autoregressive forecasts, at the longwall N-6 in the coal seam 330/2

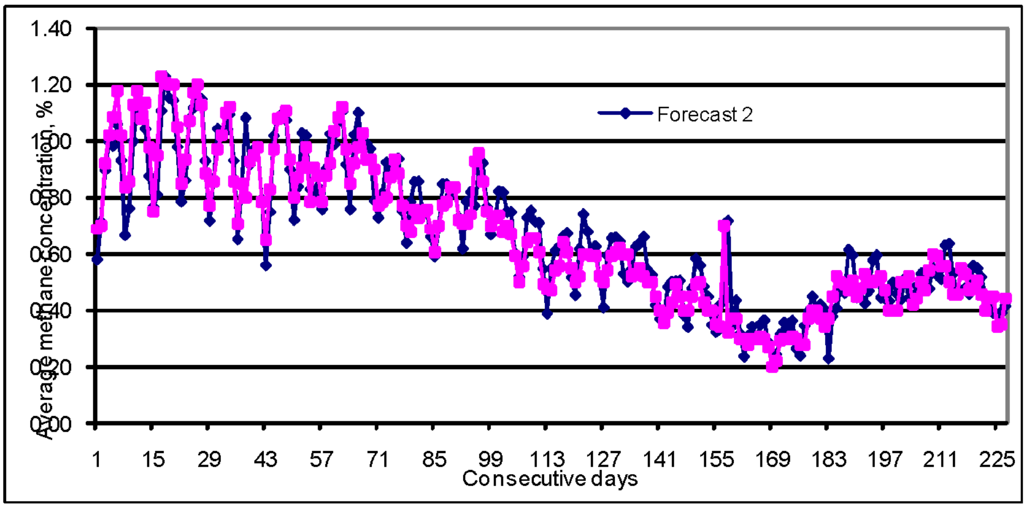

Fig. 4. Plot of measured data and cause-effect forecast of the average concentration of methane at the longwall N-6 in the seam 330/2

Table 3.
Statistical characteristics of absolute errors of the autoregressive forecast (Forecast 1)and the cause-effect forecast (Forecast 2)

Absolute errors	Average	Median	3rd Quartile	9th Decile	Minimum value	Maximum value	Total
Forecast 1	0.05	0.05	0.07	0.10	0.00	0.41	151.12
Forecast 2	0.06	0.05	0.08	0.11	0.00	0.40	152.23

Table 4.
Statistical characteristics of relative errors of the autoregressive forecast (Forecast 1) and the cause-effect forecast (Forecast 2)

Relative errors	Average	Median	3rd Quartile	9th Decile	Minimum value	Maximum value	Total
Forecast 1	9.9	7.2	12.6	18.6	0.0	129.3	2237.7
Forecast 2	10.2	8.4	13.5	18.4	0.0	124.5	2309.2

Average values of absolute errors were low and constituted 7% (Forecast 1) and ca. 9% (Forecast 2) of the average concentration of methane calculated for the whole period of observations.

According to statistical data from Table 3, it can be found that there was a slight difference in forecasts regarding values of statistical parameters characteristic for absolute errors. These values can suggest that the forecast 1 gave slightly better results.

And statistical data on relative errors presented in Table 4 also indicate slightly better results from the autoregressive forecast (Forecast 1). This is caused by a smaller sum of errors.
Another comparison of forecast errors can be based on bar charts.

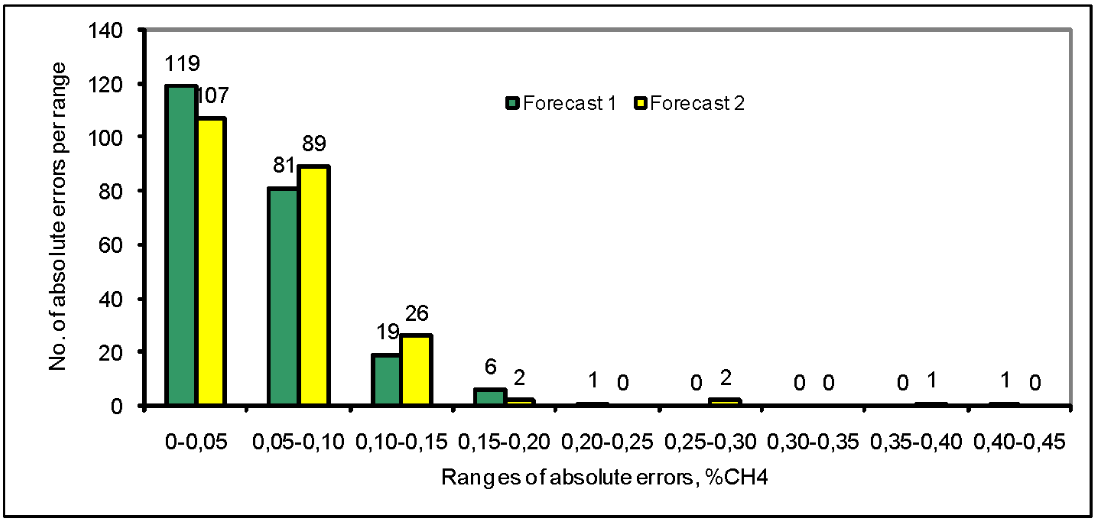

Fig. 5. Statistical characteristics of absolute errors of forecasts

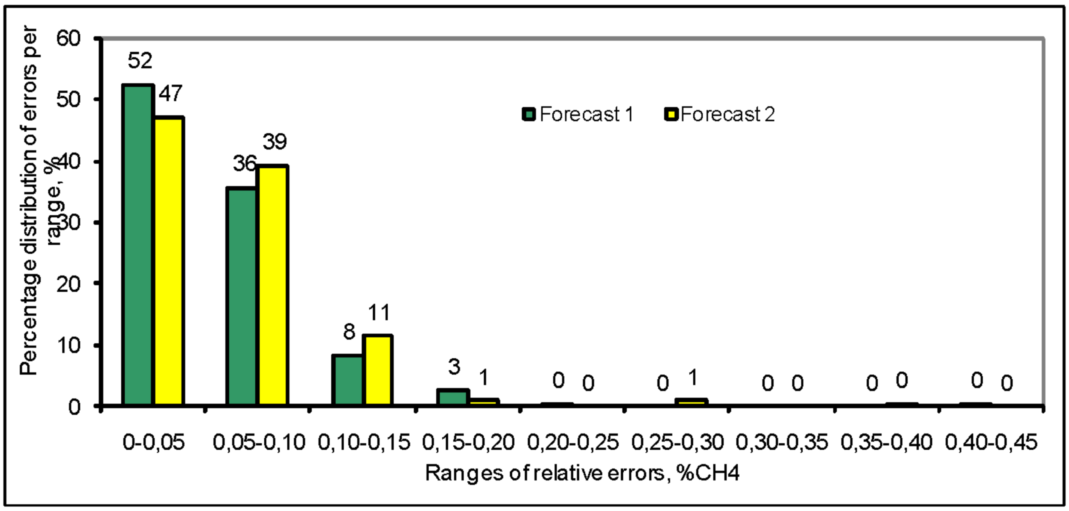

Fig. 6. Percentage distribution of absolute errors of forecast within specified ranges of errors

According to Fig. 5, within the range of absolute errors 0.00%CH_4 – 0.05%CH_4 , there 119 errors of the autoregressive forecast (52% of all absolute errors – Fig. 6), and 107 errors of the cause-effect forecast (47% of errors of that model). Within the range of errors 0.05%CH_4 – 0.10%CH_4 , there were 81 errors of the Forecast 1 and 89 errors of the Forecast 2 (36% and 39% of all absolute errors, respectively). Within the range of errors 0.10%CH_4 – 0.15%CH_4 , there were 19 and 26 absolute errors, respectively, which constituted 8% and 11% of all errors.

Fig. 7 illustrates the percentage distribution of absolute errors within the range from 0 to the specified upper limit.

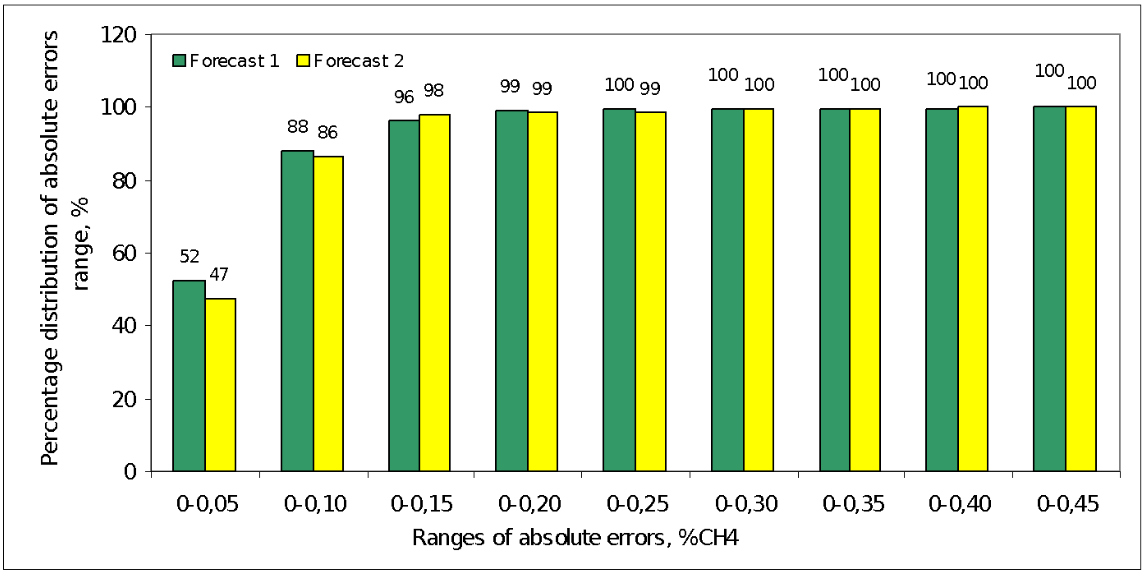

Fig. 7. Total percentage distribution of absolute errors within specified ranges

As Fig, 7 indicates, within the range of 0.00%CH_4 – 0.10%CH_4 , there were 88% of absolute errors of the autoregressive forecast and 86% of errors of the cause-effect forecast, and within the range of 0.00%CH_4 – 0.15%CH_4, there were 96% and 98% of discussed errors, respectively.

Fig. 8 illustrates the distribution of relative errors of analysed forecasts.

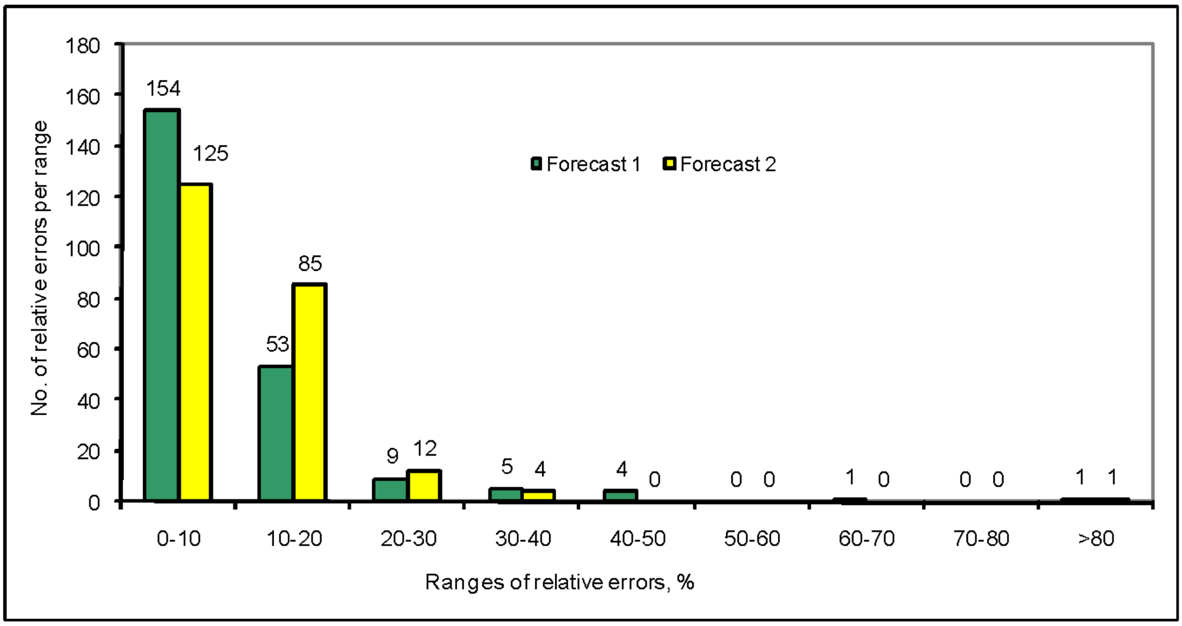

Fig. 8. Distribution of relative errors of the autoregressive forecast (Forecast 1) and the cause-effect forecast (Forecast 2)

Within the error range from 0% to 10%, there were 154 errors of the autoregressive forecast and 125 errors of the cause-effect forecast. They constituted 68% and 55% of all relative errors, respectively (Fig. 9). Within another range of 10% – 20%, there were 53 and 85 relative errors, which constituted 23% and 37% of all relative errors, respectively.

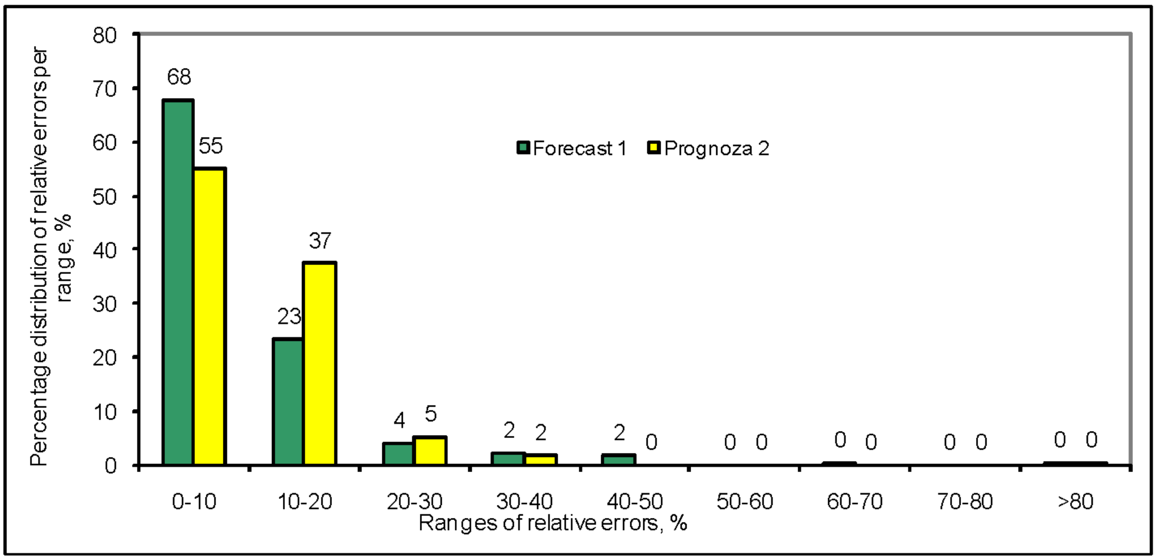

Fig. 9. Percentage distribution of relative errors in analysed forecasts within the specified ranges

Fig. 10 shows that within the range of 0% – 20%, relative errors constituted 91% of all errors of the Forecast 1 and 93% of errors of the Forecast 2.

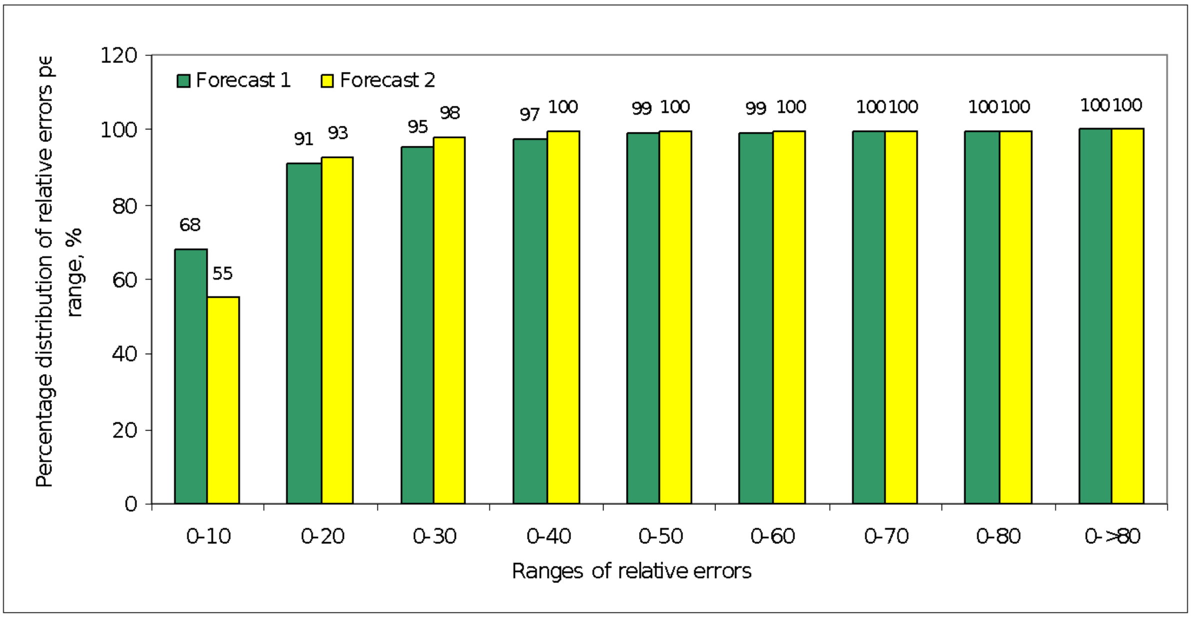

Fig. 9. Percentage distribution of relative errors of analysed forecasts

IV. CONCLUSIONS

This paper describes the application of the autoregressive and the cause-effect forecasts to perform ex post one-day forecasts of methane concentration. ThSSSSSSSSe autoregressive method used the average concentration of methane on a preceding day as the descriptive variable, and the output on the day of forecast and on the preceding days was a variable in the cause-effect method.

Prognostic models described in details in the paper by H. Badura (2013) were applied in the autoregressive method.

SAnd parameters of models for cause-effect forecasts were calculated on a current basis using the Cochrane-Orcutt method available in the GRETL software. The number of parameters of the cause-effect models was agreed while calculating their values on the basis on the probability of approaching zero. The parameter was assumed to be insignificant when the probability of approaching zero was 5% or higher.

The analysis of forecasts for the average concentration of methane at the outlet of the longwall N-6 in the seam 330/2 in the "Krupiński" mine can lead to the following conclusions:

1. The autoregressive method can be applied to prepare forecasts on the second day from starting the exploitation at the longwall.
2. To achieve sufficiently precise parameters of the cause-effect model forecast, it can be applied with some delay to the first day of exploitation at the longwall. The delay in the discussed case was 30 days.
3. Absolute and relative errors were calculated to estimate the accuracy of forecasts.
4. The average value of absolute errors, calculated for autoregressive forecasts, was 0.05%CH_4. The median was also 0.05%CH_4.
5. The average value of absolute errors, calculated for cause-effect forecasts, was 0.06%CH_4, and the median was 0.05%CH_4.
6. The total value of relative errors of the autoregressive forecast was 151.12%CH_4, and 152.23%CH_4 in case of the cause-effect model.
7. The average value of relative errors, calculated for autoregressive forecasts, was 9.9%, and the median was 7.2%CH_4.
8. The average value of relative errors, calculated for cause-and-effect forecasts, was 10.2%, and the median was 8.4%.
9. The total value of relative errors of the autoregressive forecast was 2237.7%, and 2309.2% in case of the cause-effect forecast.
10. Among forecasts with errors within the range of 0.00%CH_4 – 0.10%CH_4 , 88% of errors were from autoregressive forecasts and 86% from cause-effect ones.
11. Among forecasts with errors within the range of 0.00% – 20%, 91% of errors were from autoregressive forecasts and 93% of errors were from cause-effect ones.
12. Taking into account values of errors, both forecasts can be considered as satisfactory, and the number of absolute and relative errors defined within ranges of the forecast values can be regarded as equivalent.
13. The described forecasts can be applied for selecting short-term preventive measures considering methane risk.

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