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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION AND OBJECTIVES

Numerous coal seams contain methane. This gas, when mixed with oxygen carries a significant risk, which may lead to a catastrophic explosion that may endanger the life and health of miners and cause significant material losses. In the history of mining, methane explosions have occurred in every country exploiting coal seams saturated with methane. Such disasters have occurred in mines of Australia, China, the Czech Republic, Germany, India, Japan, Kazakhstan, New Zealand, Poland, Russia, Spain, South Africa, Ukraine and the United States. The methods of preventing this threat, developed for over one hundred and fifty years, still do not provide full protection and cause a significant increase in costs and limitations in production. Statistics show that ever increasing working depths in coal mining is resulting in significant increases in methane emissions (www.cdc.gov/niosh/mining/statistics/default.html), leading to heightened health and environmental risks at production faces.

Furthermore, such occurrences also affect productivity at longwall complexes in coal mines (Schatzel et al., 2008). Emergency power shutdowns caused by excessive methane levels imposed by the safety regulations in most countries reduce the hazard of gas explosions, but lead to huge losses due to work and time-consuming procedures of safe restart of mining. Restoring safe conditions must be monitored not only at the longwall face but at all possible paths of its removal through the ventilation system.

Developments in modern technology have brought about significant changes to the control of longwall complexes in modern coal mines, including the possibility of remote control and positioning of operators at a safe distance from machines. Contemporary solutions developed by R&D teams at world's leading shearer manufacturers, such as Eickhoff (www.eickhoff-bochum.de), Joy (www.mining.komatsu) and Caterpillar (www.caterpillar.com) have introduced effective control systems to maximize output. Currently, algorithms for automatic control of longwall complexes consider mining and geological conditions as well as technical parameters of applied devices and systems. However, these developments have not yet addressed or helped in controlling hazards associated with excessive methane emissions. The PICTO project shows opportunities to improve safety and efficiency in this area.

Current state-of-the-art knowledge has demonstrated that there is sufficient background and technological base **to develop a closed loop system to monitor the longwall environment (methane emission and drainage systems, as well as ventilation) and control or regulate coal production and machine operation schedule, at longwall and LTCC faces to eliminate excessive gas emissions and mitigate against risks at the face**. Results of the PICTO project, described in this monograph are a significant step towards achieving this objective.

The diagram, shown in Figure 1 presents the Project Concept. At the first stage the production, machine preformance and uncerground environment data has been collected. Then this data has been processed to privide input for further acivites, namely:

- Modeling of the longwall gas emission from surrounding strata and goaf
- Modelling the airflow and gas migration at longwall in connection with the operation of the shearer

- Development and calibration of so-called Virtual Longwall Models which are a kind of “digial twins” of real underground excavation system
- Development and testing of the target shearer operation control procedures.

Finally prossibility of controlled operation has been demonstrated and its advantages have been estimated.

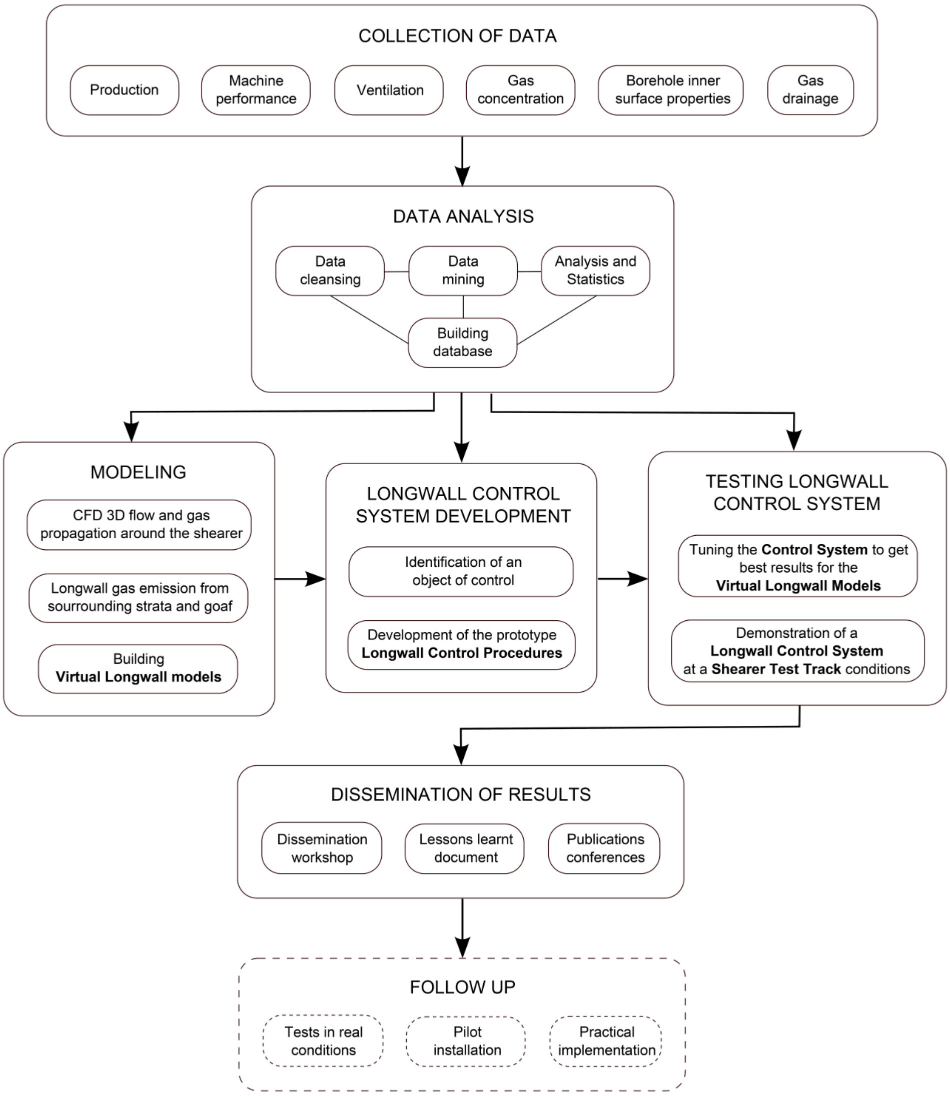


Figure 1. A block diagram of the Project Concept

The project objectives have been achieved through:

- Systematic monitoring of longwall face ventilation conditions at single slice and LTCC faces to characterize gas concentrations along with monitored shearer and AFC performance indicators at production faces through field experimental work to optimize face monitoring and environmental control designs.
- Systematic monitoring of gas drainage performance of single and group of boreholes at longwall faces to characterize the patterns of gas emission from roof, floor and goaf

sources through field experimental work and numerical modelling to optimize face and tailgate gas monitoring and environmental control designs.

- Data processing and development of calibrated virtual models of single slice longwall and LTCC faces using the findings of 1&2 above and model implementation in Ventgraph software.
- Development of new shearer control procedures/algorithms to regulate shearer operations using calibrated virtual longwall environment/operation computer models in Ventgraph
- Integration, testing, validation and demonstration of the shearer and longwall production systems' control procedures/algorithms using specific shearer control hardware and software provided by the Project's partner Eickhoff.

The project has been realised by a consortium shown in Figure 2, consisting of six different partners from four European member states representing research organisations, universities, major coal producers in Europe and a coal mine longwall face machinery manufacturer during a period of forty two months.

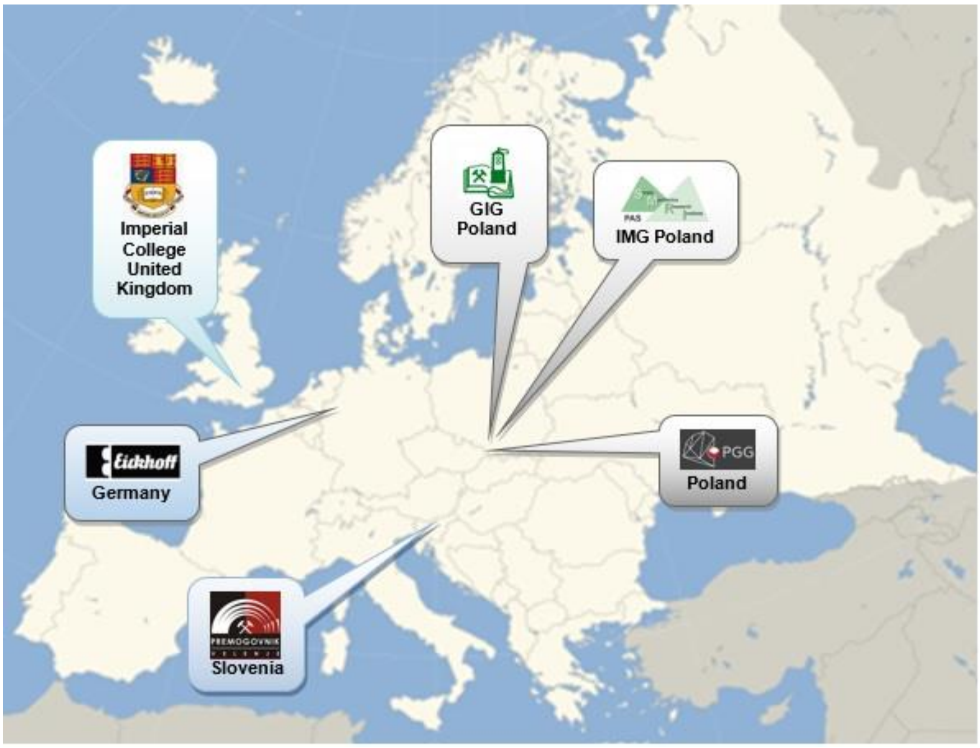


Figure 2. The PICTO project consortium

Following chapters present selected results of the actions listed above

2. FINDINGS FROM SYSTEMATIC MONITORING OF ENVIRONMENTAL CONDITIONS AT THE FACE

During the early stages of the project, research teams set up a monitoring plan at both the PGG Jankowice colliery and at Coal Mine Velenje, which represented the two different longwall production methods as well as ventilation layouts commonly employed at these two mines.

2.1. Jankowice colliery methane mission monitoring at longwall Z-11, seam 408/1

As Figure 3 illustrates, the single slice retreating longwall mining employed at Jankowice colliery practices methane drainage and often uses Y-ventilation layout to combat high rates of gas emission experienced due to deep mining conditions and high *in situ* gas content of the coal seams mined. The production at the face was using an Eickhoff (SL-300/EP) shearer.

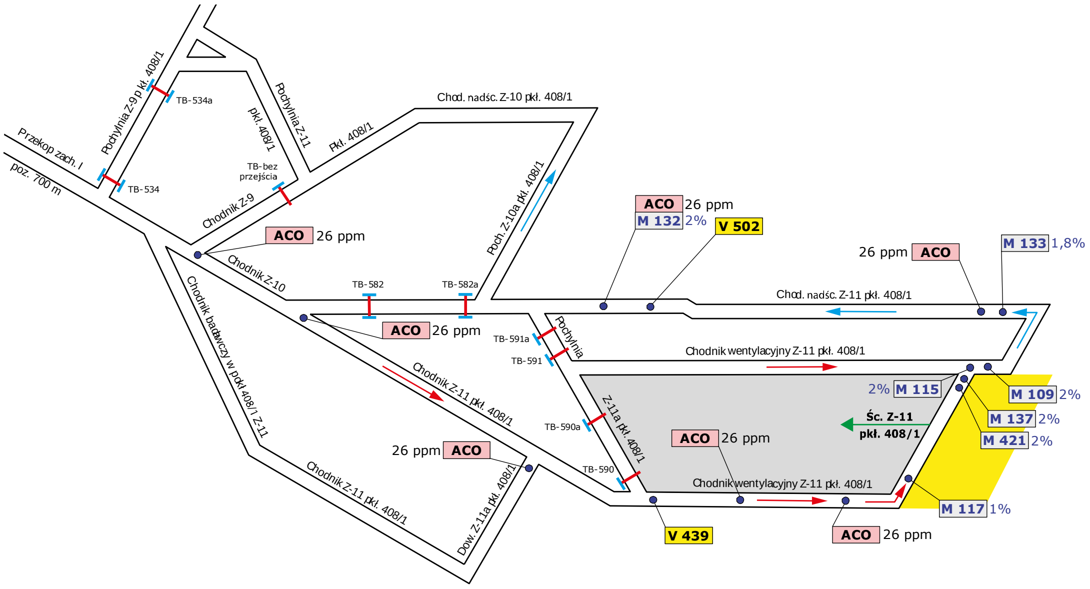


Figure 3. Ventilation layout at Z-11 longwall in seam 408/1 with the methane and airflow sensors

The analysis of a 24-hour long production period monitored in February 2019 presented here as an example to demonstrate the gas emission characteristics at longwall face Z-11 due to coal production, and the methane percentage readings at different methane sensors.

In *Figure 3*, fresh air enters the retreating longwall face Z-11 (Gray shaded area) through both gateroads, the total volume monitored by V439 and V502 airflow sensors. Contaminated air at the face is monitored by a number of methane sensors M117, M421, M137 at the face, sensors M115 and M109 monitor methane at the at the face exit where supplementary fresh air ventilates the face end, aimed at pushing the goaf gas away from the AFC motor at that point, and M 133 and M 132 monitors methane concentration at the tailgate. The % concentration values in Figure 3 indicate the maximum level these sensors are set to trip the power supply to the face.

It is well known in coal mining (and also demonstrated by CFD modelling in Task 2.4) that shearer moving in a longwall disturbs ventilation at the face, affect both air flow and methane concentration in its surroundings. The change and the extent at which the airflow and methane concentration changes also depends on the relative movement of the shearer with or against the direction of airflow. As Figure 4 demonstrates, methane concentration at the face end and in the tailgate sensor M133 increases as the shearer gets closer to the face end (the light blue line denotes the shearer position in terms of the shield number).

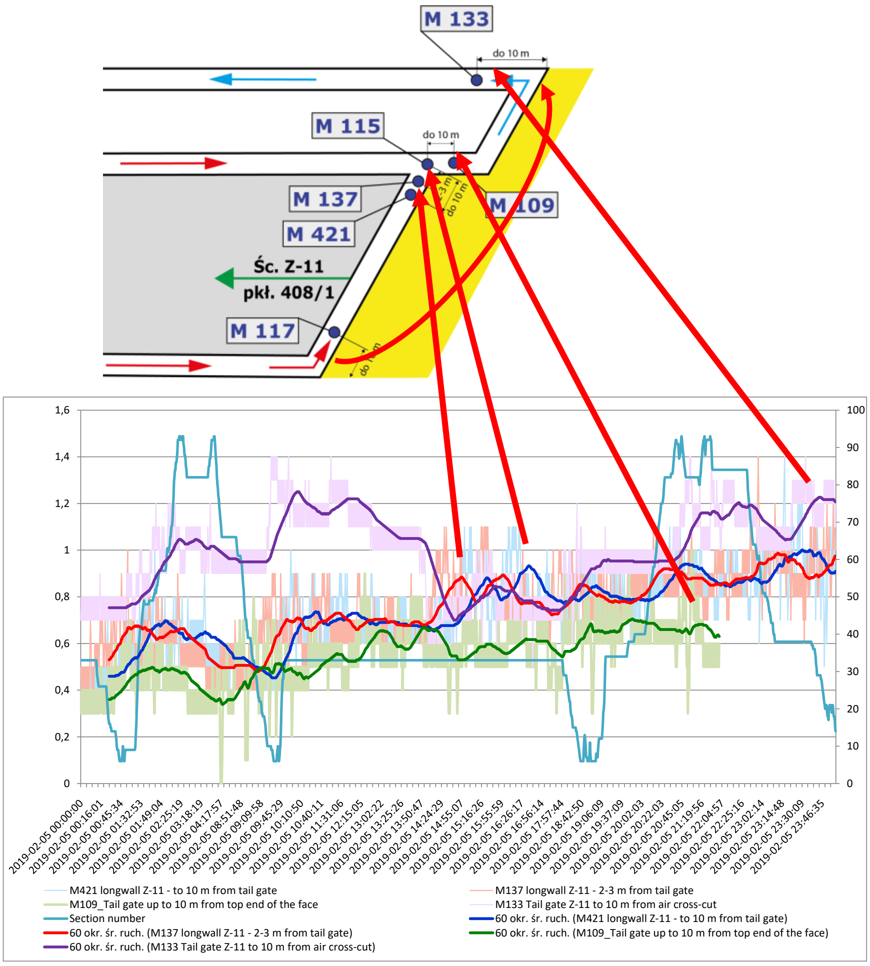


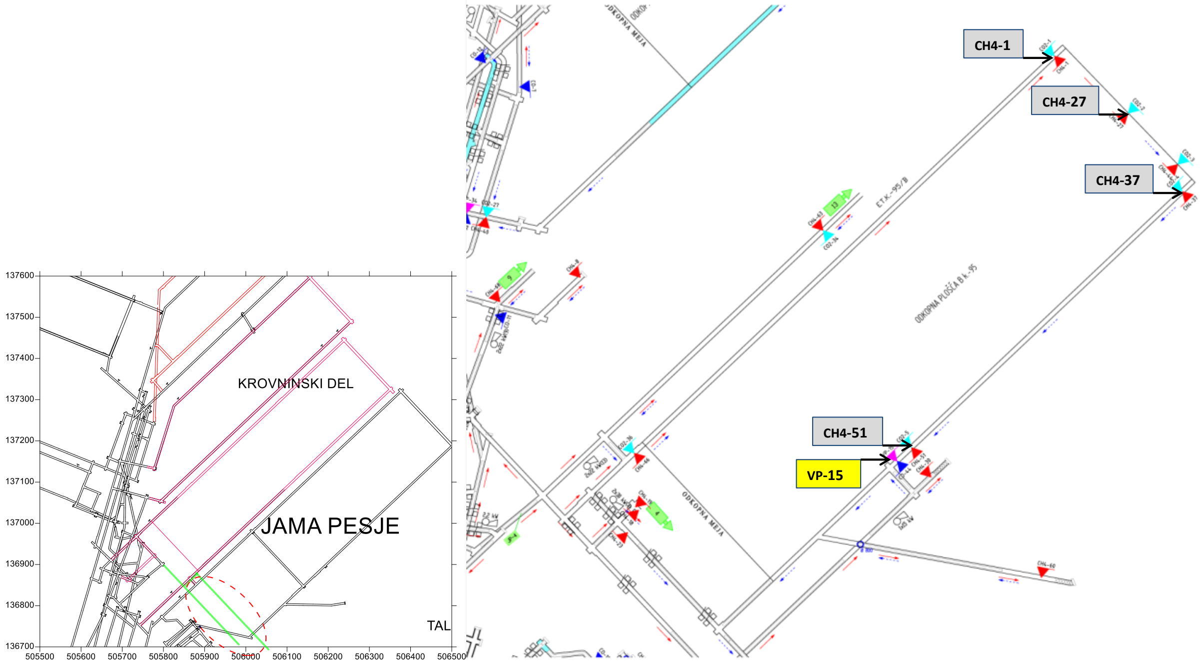
Figure 4. Methane concentration readings at different sensors along the Z-11 longwall face throughout the production day.

Figure 4 also illustrates that methane sensor M133 often has the highest methane concentration, especially when the shearer is close to the face end, as goaf gas is pushed towards this sensor. This example also demonstrates the objective of the use of Y-ventilation layout at coal mines.

2.2. Coal Mine Velenje methane mission monitoring at longwall B k.-95

Coal Mine Velenje employs retreating multi-slice Longwall Top Coal Caving method in their ultra-thick lignite seam with a relatively lower gas content but much higher extraction height (up to 17 metres). The do not practice methane drainage, and employ mostly the U-ventilation layout (Figure 5).

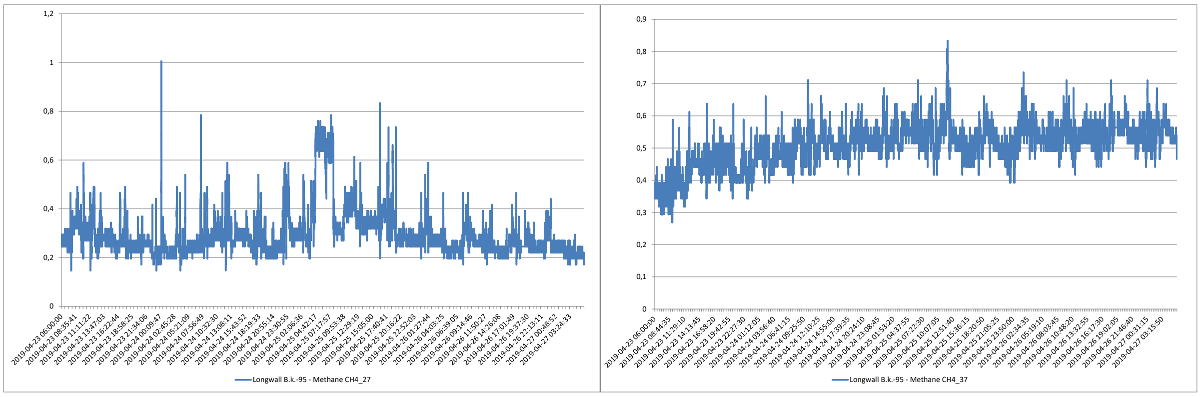
As planned at the start of the project, methane concentration and shearer movement at two LTCC faces D k.-95 and B k.-95 (Figure 5b) were monitored during April and June 2019. Here the face B k.-95, which also was the site of underground multi sensor (MethAnemometer) measurements were taken will be discussed as an example.



(a) (b)

Figure 5. (a) U-ventilation layouts commonly used at LTCC faces in Coal Mine Velenje, (b) Methane and airflow monitoring sensors at B k.-95 LTCC face

At LTCC face B k.-95 fresh air enters the face at point where methane sensor CH_4-1 is located in Figure 5b and leaves the face from the tailgate near sensor CH_4-37 is. Sensor CH_4-51 at the end of the tailgate normally serves as the one set to trip power supply to the face if the maximum allowable methane concentration is exceeded as the tailgate can potentially pick up some more methane from a neighbouring mined out face (goaf) or their roof goaf. Figure 6 illustrates the B k.-95 LTCC face methane emission monitoring data collected during 23-27 April 2019 from methane sensors CH_4-27 and CH_4-37, confirming that the ventilation air pics up more methane as it travels along the face.



(a) (b)

Figure 6. Coal Mine Velenje B k.-95 LTCC face methane emission monitoring data collected during 23-27 April 2019 from (a) methane sensor CH_4-27 and (b) methane sensor CH_4-37

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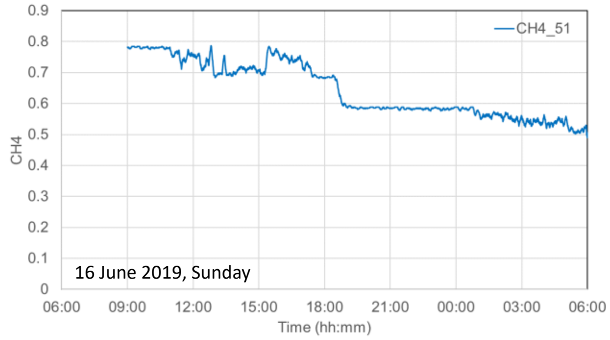
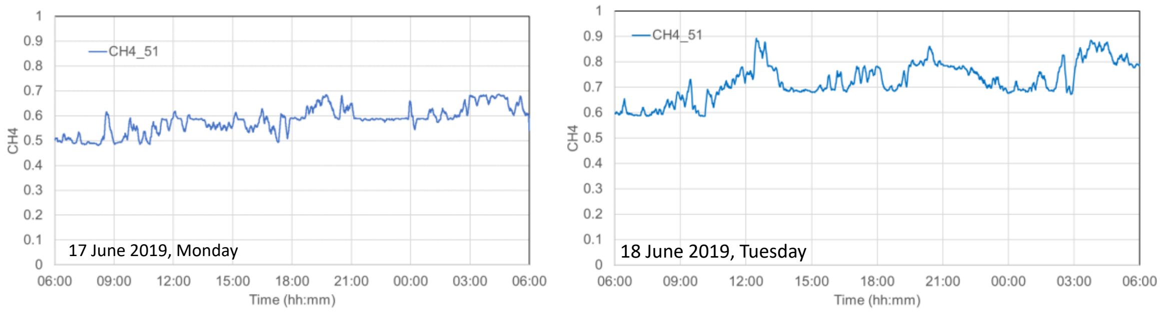


(a)



(b) (c)

Figure 7. Coal Mine Velenje B k.-95 LTCC methane concentration monitoring data collected during 16-18 June 2019 from the tailgate methane sensor CH_4-51

Figure 8 illustrates how methane emission rates, therefore the general body methane concentration, increases during the week. On Sundays, when there is no production, the level drops to its minimum value and, as morning shift starts on Mondays, the emission and therefore the concentration starts rising. This trend normally continues during the week and highest levels are reached on Friday, unless of course the maximum allowable limit is exceeded and the production is halted.

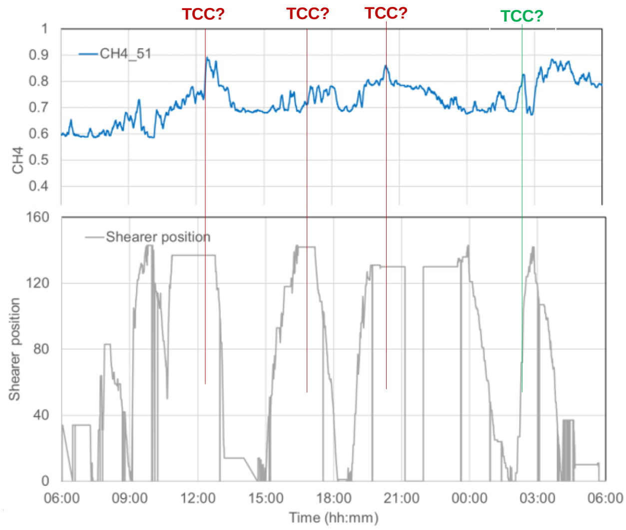


Figure 8. Coal Mine Velenje B k.-95 LTCC methane concentration monitoring data collected during 3 working shifts on 18 June 2019 from the tailgate methane sensor CH_4-51 and their correlation with shearer movement.

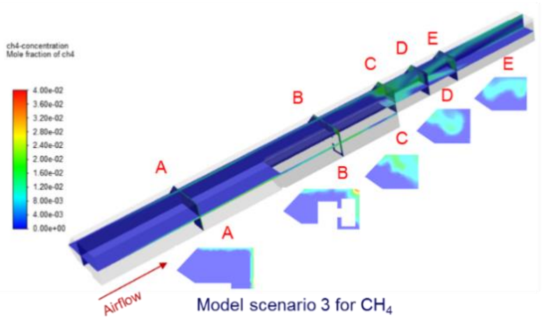
Similar to the variable nature of coal production and methane emission rates during a week, coal production during the week is not steady state. Methane emission increases at a steady rate as longwall shearer transitions from a stationary state to production mode and, in the case of Coal Mine Velenje, an additional process of caving the top coal takes place, which affects emission rates and increases methane concentration in the longwall district while the shearer is stationary. Figure 8 illustrates the correlation between machine movement and/or stationarity while top coal caving and increased gas emission rates due to increased exposure to caved top coal and roof goaf. Such fluctuations are also captured by the strategically placed tailgate sensor CH_4-51

3. CFD MODELLING OF LONGWALL PRODUCTION AND METHEN EMISSION

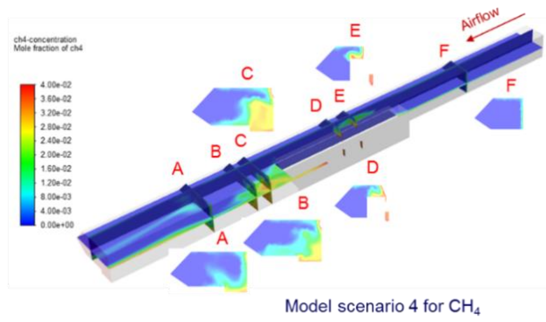
The same two longwall faces B k.-95 at Coal Mine Velenje and Z-11 at Jankowice colliery where gas concentration monitoring was carried out in WP2 were used for CFD modelling of airflow and methane emission simulations.

3.1. CFD model for the B k-95 LTCC face at Coal Mine Velenje

The Bk.-95K LTCC face at Coal Mine Velenje (Figure 3b) CFD model was constructed using a 3D scan of the face, shearer and shield support dimensions. Figure 9 presents the methane concentration contours around the longwall face for two model scenarios, when the ventilation air flow is either in the opposite direction (Figure 9a) or in the same direction (Figure 9b) with the shearer movement. It is clear that in the second scenario, the shearer creates a shadow zone downwind of airflow direction, in front of the cutting head, where methane concentration is the highest and can exceed allowable limits in a small area.



(a)



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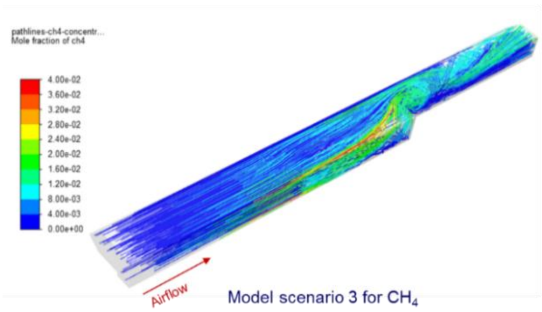

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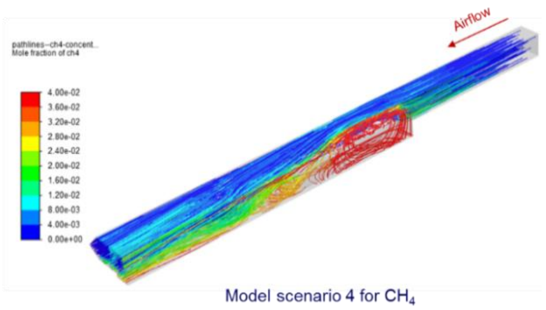


(d)

Figure 9. (a) and (b) Contour map of methane concentration along the B k.-95 longwall face considering the ventilation airflow direction as a variable, (c) and (d) Pathlines of methane concentration along the B k.-95 longwall face for the same

Pathlines of methane concentration around the longwall face for the scenarios in Figure 9(a) and (b) confirm the same observation with a much stronger visual evidence. Depending on the shearer's location and airflow direction, maximum methane concentration is found in the shadow zone of the shearer, downwind of airflow. Of course, it is common knowledge that shearer designs account for this with the necessary mitigation measures against ignition of methane at the cutting head.

The second set of CFD models of the Bk.-95K LTCC face at Coal Mine Velenje considered three different positions of the sheared in the longwall face, near the main gate, centre of the face and near the tailgate, as well as including methane sources as the face, roof, floor, the goaf and the two cutting heads/drums in the shearer as contributors to the total rates. Figure 10 presents the methane concentration for these three model scenarios. The results confirm increased General Body methane concentration along the longwall face towards the tailgate, ranging from zero to ~2.0% at different points depending on air quantities and emission rates. Methane levels tend to concentrate close to the gas emission sources (in particular the face and roof close to the two operational drums) and in the shadow zone of the shearer downwind of airflow direction.

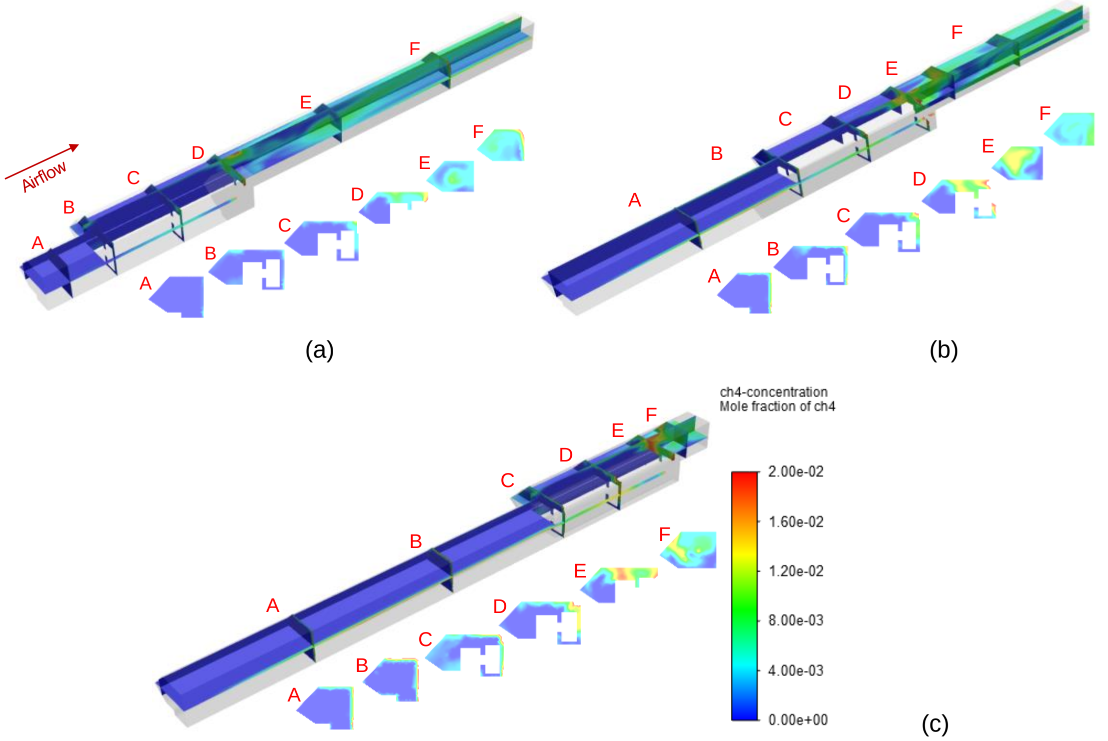


Figure 10.Contour map of methane concentration along the B k.-95 longwall face for different shearer locations at Coal Mine Velenje: (a) shearer close to the fresh air intake, (b) shearer in the middle, and (c) shearer close to the out bye/tailgate end of the longwall face section

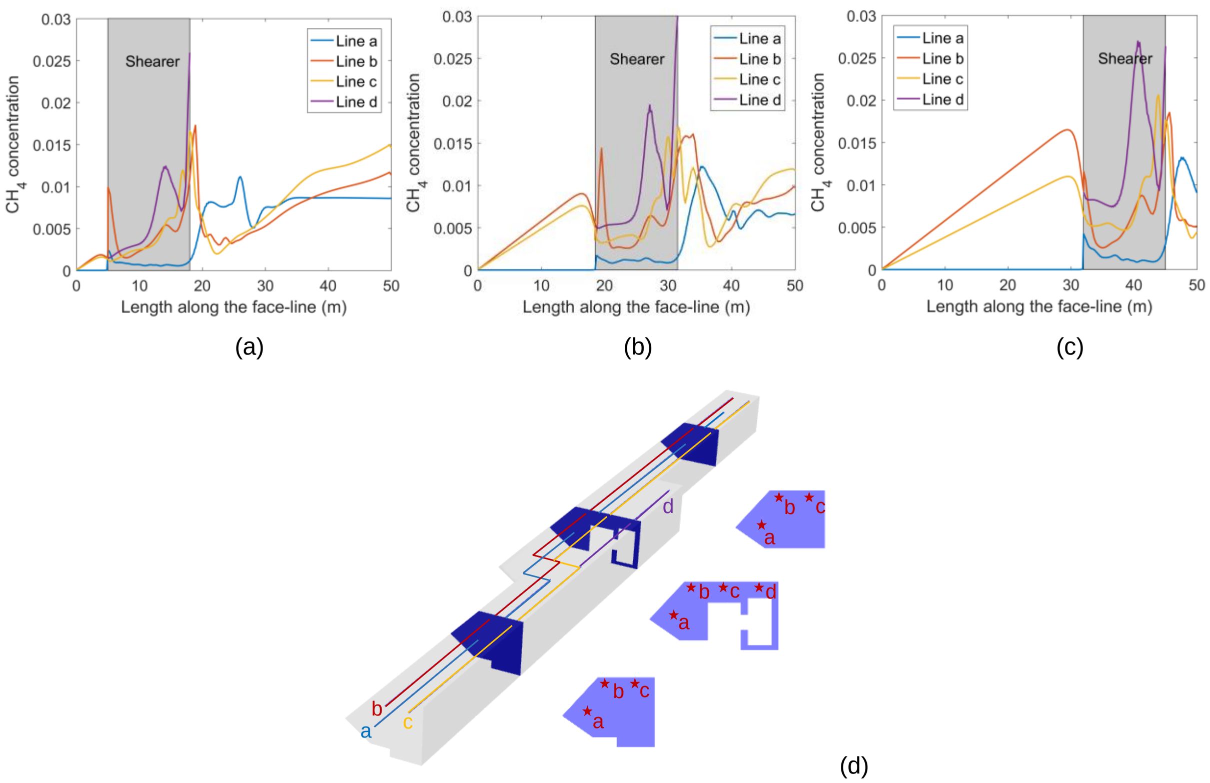


Figure 11. Methane concentration at selected monitoring points (d) along the B.K.-95 longwall face for different shearer locations at Coal Mine Velenje: (a) shearer close to the fresh air intake, (b) shearer in the middle, and (c) shearer close to the out bye end of the longwall face close to the tailgate

It was found that, compared to methane release from longwall face and roof, that from goaf areas and floor has a negligible impact on the methane concentration across the longwall face section.

The findings of the modelling summarised in Figure 11 illustrate that methane concentrations along the lines defined by “b” and “c” under the hydraulic support canopy increases steadily from zero to a much higher than the mean (General Body) values for each position of the shearer due to low air quantities at these areas. The General Body methane concentration monitored along line “a” after the shearer is close to the values recorded by Coal Mine Velenje’s own methane detectors installed at the face (Section 3.2 above). When the shearer is much closer to the out bye/tailgate end of the longwall face this value exceeds 1.0% due to the position of the shearer and the face end effects.

3.2. CFD model for the Z11 longwall of the Jankowice mine

The CFD modelling of longwall Z-11 investigated airflow and gas concentrations at the face as well as at the tailgate of the so-called “short Y” system of ventilation layout (Figure 12).

In “short Y” system of ventilation layout the contaminated air from the face is being directed back towards the goaf area, via chain pillars or a curtain constructed (back-return). This ensures that the goaf gas is pushed back in the waste zone. However, by doing so, the air column collects more gas from the goaf, as well as roof and floor source seams.

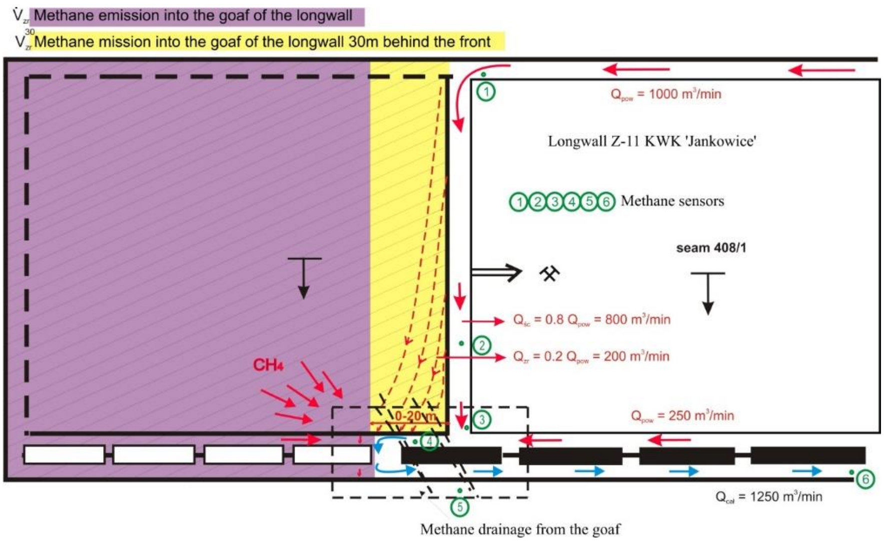


Figure 12.Conceptualisation of the air distribution and methane sensors at the as modelled for “short Y” system of ventilation layout representative of longwall Z-11

In order to investigate the effect of the position of the shearer on gas concentration at different parts of the face, three scenarios were modelled in CFD for the U type of ventilation at the Z11a Jankowice longwall (Janoszek and Krawczyk 2022). Shearer near the main gate, in the centre of the face and at face end near the tailgate. Model runs for all the scenarios were analysed and found that, as in the field measured concentrations at sensors, gas concentration along the face increased towards the face end, reaching its highest level at the face end (Sensor 4) and further gas release from the goaf and at tailgate pushed the methane towards the Sensor 6 location, which recorded the highest rate of methane concentration (Figure 13), conforming the recorded data during long-term monitoring using the mines' sensor system earlier in the project. Another observation made from the CFD simulations was that, closer the shearer to the face end/tailgate junction, the higher the recorded methane concentration at sensor 6 location. Figure 13b represents the values for this scenario.

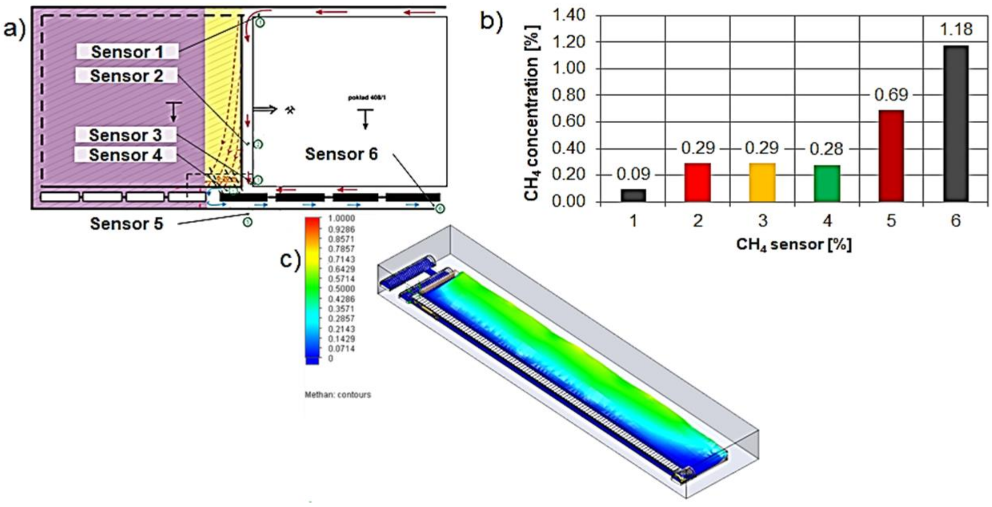


Figure 13. The modelled distribution of methane concentration changes along the face when the shearer is at the face end near the tailgate: a – the Z-11 longwall face model and the layout of sensors arrangement, b – change in methane concentration distribution along the face towards the tailgate, c - map of methane mass share

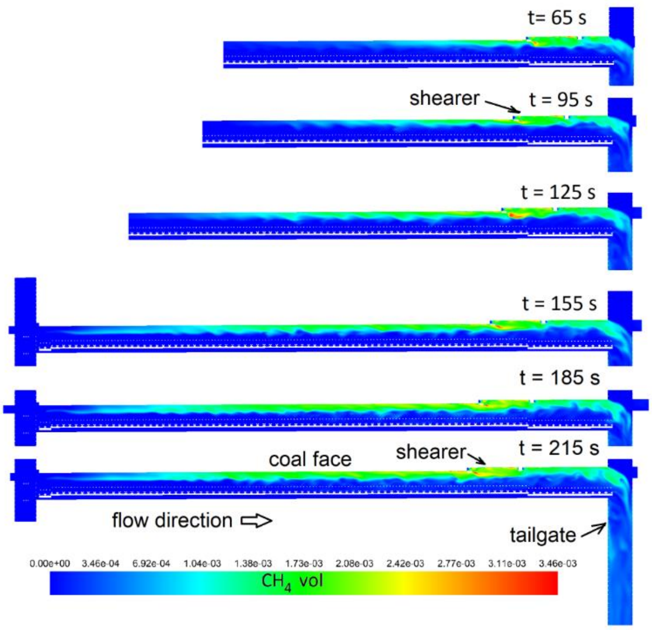


Figure 14. Time series distribution of methane concentration at mid height of longwall after the shearer positioned at the face end/tailgate junction starts cutting coal and travels in the opposite direction to airflow in a longwall face

Further CFD analysis using the Jankowice colliery Z-11a longwall district model included the assessment of the time it takes for methane concentration to reach steady state throughout the full length of the longwall face when the shearer movement is against the flow of ventilation air in the longwall face. As Figure 14 illustrates, the model results suggest that it can take up to 2 minutes for the methane concentrated air to reach the main gate, much longer than anticipated. These results also are in agreement with the CFD modelling carried out using the Coal Mine Velenje layout at LTCC B k.-95 with respect to the airflow direction and the position of the cutting drum.

3.3. Conclusions from in situ systematic monitoring and CFD modelling of methane concentrations

Overall, the CFD simulations using both the Velenje and Jankowice layouts have confirmed the systematic monitoring data collected earlier in the project. Both mines use a set of strategically located methane and airflow sensors in the longwall district. Methane sensors, in particular, are distributed along the longwall faces as well as being placed at the tailgate as normal practice. These are picking up the increasing pattern of gas concentrations along the face towards the tailgate and methane entering the tailgate either from the goaf in Y-ventilations layouts at Jankowice or from neighbouring goafs and the roof goaf in U-ventilation layouts at Coal Mine Velenje. In both cases the maximum methane concentrations are measured/modelled at the tailgate. Field measurements and CFD modelling have also identified that roof level concentrations of methane below the shield support canopy are relatively higher, and should be considered as the optimum positions for the sensors if practicable.

4. BOREHOLE PROBING AND DRAINAGE MONITORING IDENTIFYING THE SOURCES OF METHANE EMISSIONS

Task 3.2 in WP3 focused on current and past drainage monitoring data to establish the source of methane and its flow patterns in the roof and floor around longwall faces at the two partner mines. The Jankowice colliery practices methane drainage employing a leapfrog system of drainage ranges, with the group of drainage boreholes angled towards the goaf above the longwall face as it passes under the boreholes, as illustrated in Figure 15.

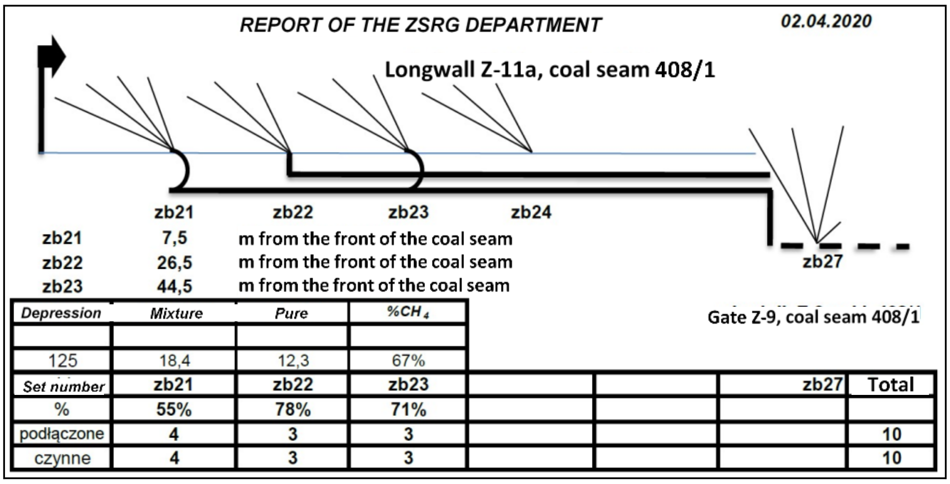


Figure 15. Methane drainage layout at Z-11 retreating longwall face at Jankowice colliery

Continuously monitored drainage data with the ZCO sensor in the boreholes provided a good sense of the effective drainage zone from source seams above the production horizon.

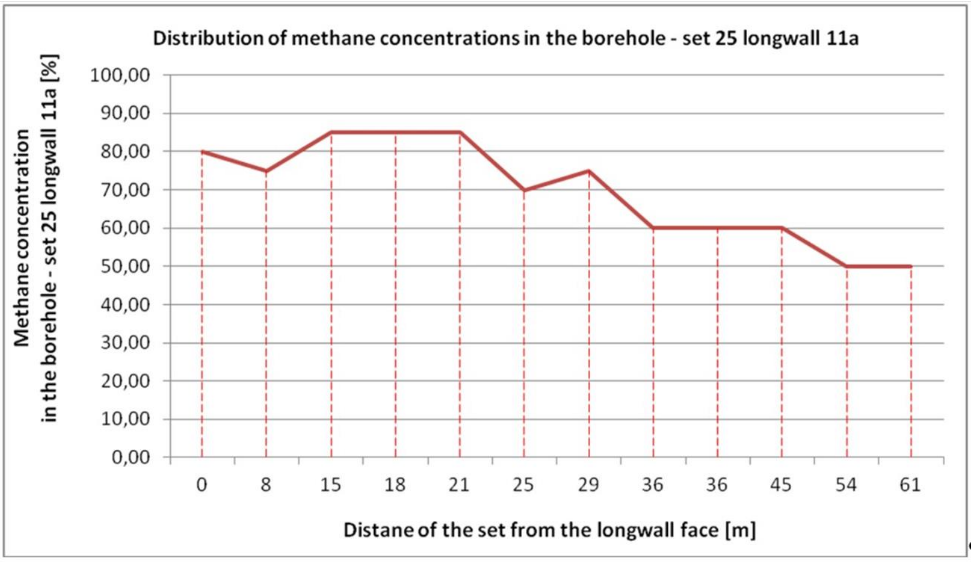


Figure 16. Distribution of methane concentrations registered with the ZCO sensor in drainage boreholes

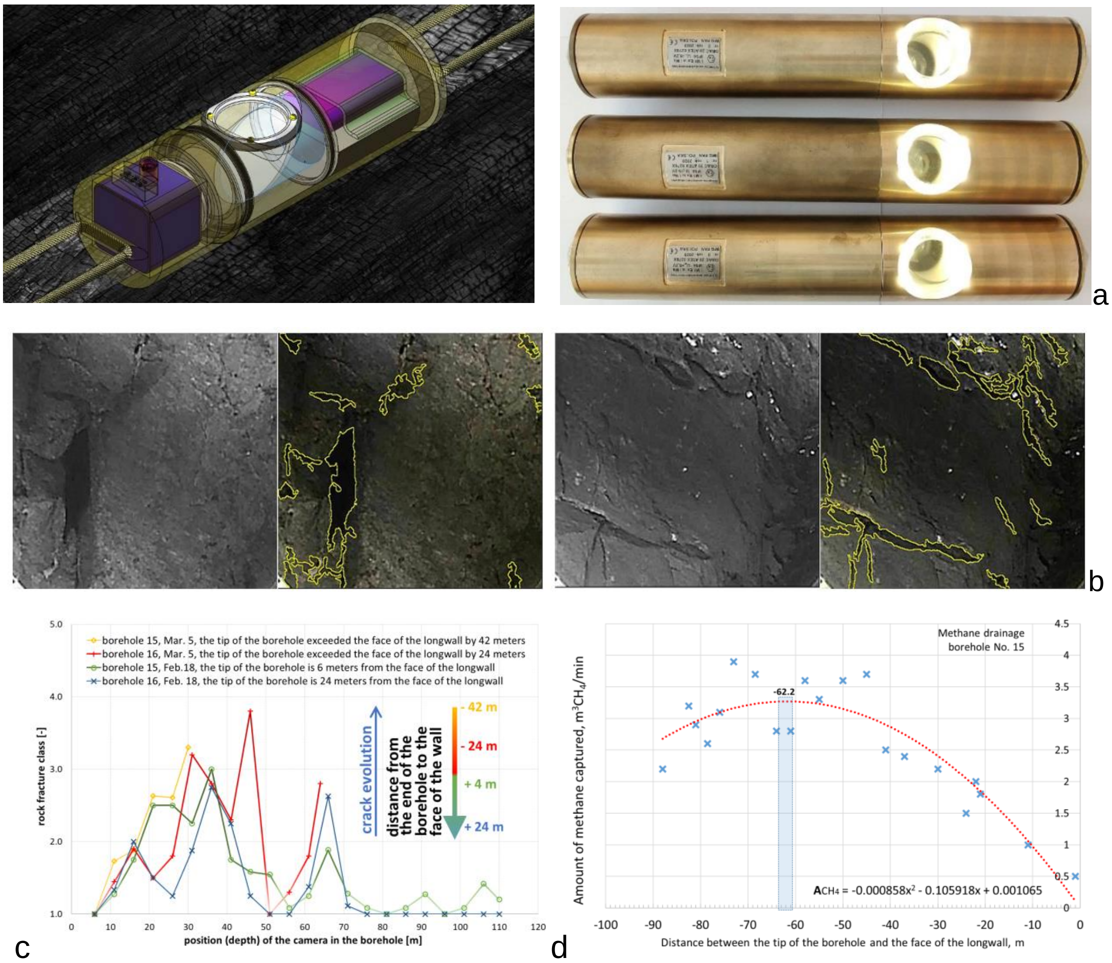


Figure 17. Visual inspection of internal borehole surface probing, a- dedicated borehole probe, b- computer image analysis, c- distribution of rock fracture classes for two boreholes and two positions of longwall, d- relationships of borehole output and longwall face position

Figure 16 presents monitored methane concentrations in one example borehole set, where the highest concentrations are achieved when the boreholes were around 10 to 30 metres behind the faceline above the goaf.

Visual inspection of boreholes (Figure 17), done by a dedicated probe developed at IMG-PAN for the project needs provided infromation on relationships of the crack distribution and the longwall face position.

The analysis of all the methane drainage monitoring from the Z-11a longwall district using the 'Y' ventilation system has shown that methane drainage rate was enhanced within the 50 metre zone behind the face, after which they were not as effective. The two main emission sources at Jankowice colliery were identified as the mined seam and the roof and floor seams within the gas emission zone formed

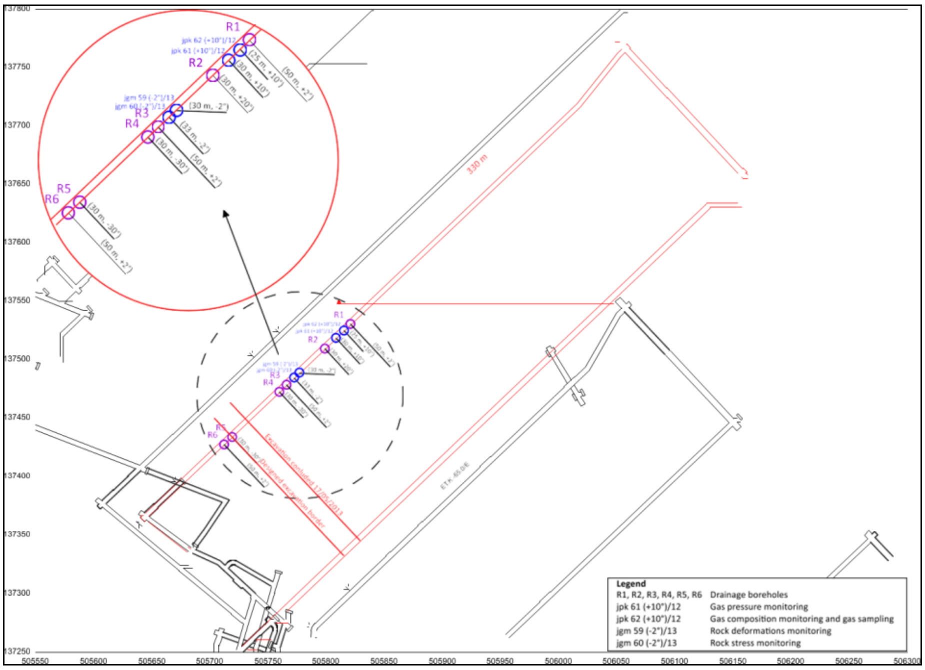


Figure 18. Locations of gas drainage and seam gas pressure-composition-rock stress and deformation monitoring boreholes used during the CoGasOUT pilot drainage trials at Coal Mine Velenje

Coal Mine Velenje does not practice methane drainage, however, they had past field trials which were monitored in previous projects (Figure 18). Re-analysis of these data from the three successive trails have shown that:

- Due to the low permeability of Velenje lignite, the initial total gas flow rate was too low (~3 m3/h) and very difficult to be measured unless the borehole tip is not within 40 metres of the approaching coal face.
- It was observed that enhanced permeability zone for horizontal in-panel boreholes in LTCC faces may start at around 30 metres from the longwall face, while the floor boreholes may experience permeability enhancement as far as 40 metres ahead of the coal face.
- Maximum drainage rates from the drainage boreholes were recorded when the longwall face is around 20 metres away from the boreholes.

- If kept fully open in the already fractured TOP COAL, roof boreholes were believed to have higher productivity.
- If kept fully open in the fractured floor (depending on the borehole inclination and level of mining) floor boreholes may also have an advantage over in-panel boreholes as they can be kept open even after the faceline crosses their position and drain behind the faceline.

5. NUMERICAL MODELLING OF FACE EMISSIONS OF METHANE AND METHANE DRAINAGE PERFORMANCE

The second kind of numerical modelling aimed at investigating the gas flow patterns and sources of gas emission at longwall and LTCC districts and focused again on the two test sites at Coal Mine Velenje and Jankowice colliery. A two-way coupled flow-geomechanical models have been implemented in ECLIPSE and FLAC^{3D} (**Figure 19**) to first model the stress and permeability variations, as well as failure zone development due to coal excavation.

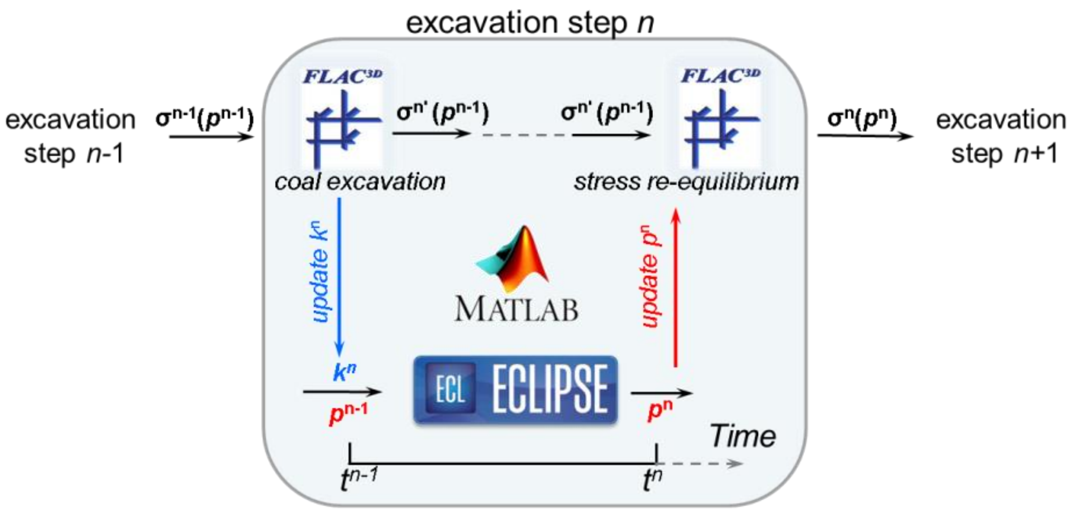


Figure 19. Coupling workflow of FLAC3D and ECLIPSE (modified after Rutqvist and Tsang, 2003)

Initially, the coupled approach was implemented to the B k.-95 longwall top coal caving (LTCC) panel at Coal Mine Velenje to simulate gas emission and concentration. Permeability and pore pressure are used as coupling parameters between geomechanical and flow simulators. The Imperial College permeability model was incorporated in the coupled model which incorporates the effect of stress disturbance due to effective stress change. The face gas emission rate and concentration are analysed and compared with monitored data at Coal Mine Velenje as the mine does not currently practise gas drainage.

Then, the coupled model was applied to investigate the performance of cross-measure roof/floor and in-seam/panel boreholes in thick seam LTCC panel layouts, using Coal Mine Velenje as an example. Based on the Coal Mine Velenje gas emission model, five sets of cross-measure and in-seam boreholes were modelled and the gas drainage performance was analysed

5.1. Evaluation of gas emission from roof goaf, mining level and floor coal

As described in detail in Deliverable report D3.3 part of the numerical modelling effort using the Coal Mine Velenje model aimed at identify the sources of gas emission at their LTCC faces. Using the B k-95 LTCC panel layout, the origin of gas released into the face was tracked over a simulation period. The flow rates of gas migrating from the roof goaf, mining level and floor coal are plotted in Figure 20. It was found that that the rate of gas emission from the mined coal is strongly affected by the coal face advance/retreat rate. The higher the production rate, the higher is the volume of gas emitted in that day. In contrast, floor coal and roof goaf act as a steady gas source accounting for a considerable part of the total gas emission, which was found to be approximately 50%.

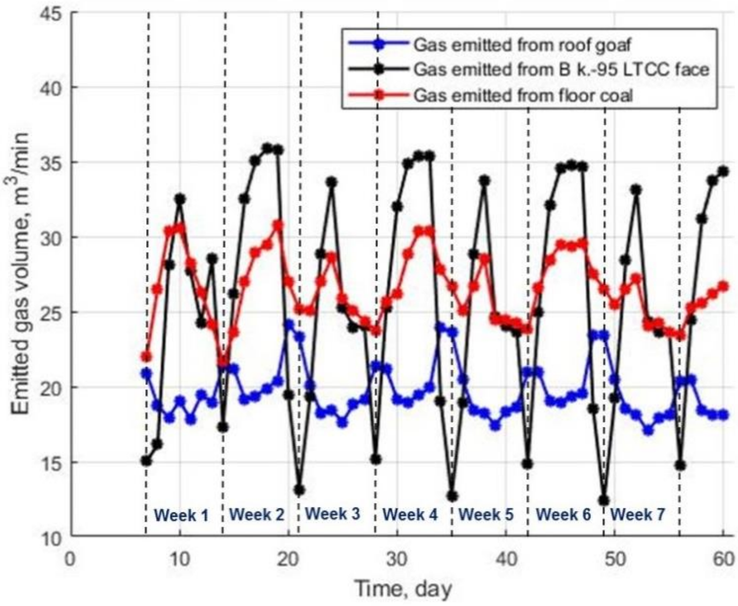


Figure 20. Emitted gas volume from different emission sources (roof goaf, mining level and floor coal) into the production face at Coal Mine Velenje.

5.2. Numerical modelling of drainage boreholes, performance, and sources of methane emission

Numerical modelling of drainage boreholes at Coal Mine Velenje aimed at comparing the performance of in-seam, roof and floor boreholes targeting the main sources of gas other than the mining horizon. Figure 21 presents a comparison between the performance of the three boreholes of different orientation, confirming the observations from the pilot drainage trials summarised above. The reason that the roof borehole is more productive than horizontal boreholes and floor boreholes is be the existence of a 15 m think top coal with a relative higher permeability due to being overmined at the previous mining level above. This suggests that, as multi-slice LTCC extends deeper and deeper, coal production at each mining level affects seam gas pressure and permeability in the level below, also affecting emission and drainage rates.

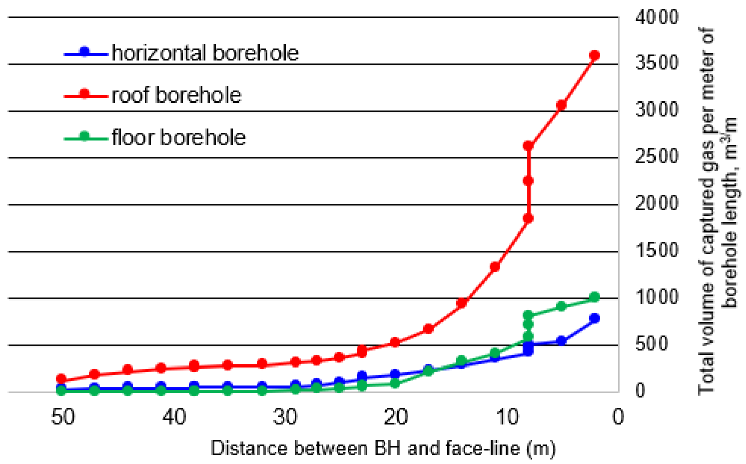


Figure 21.Performance comparison of three different drainage borehole options in Velenje Mining Method of LTCC.

The Jankowice drainage numerical model simulated a similar borehole layout as in Figure 15 and examined the roof seams as ethane sources contributing to emissions in to the face and the goaf and/or the tailgates under favourable conditions.

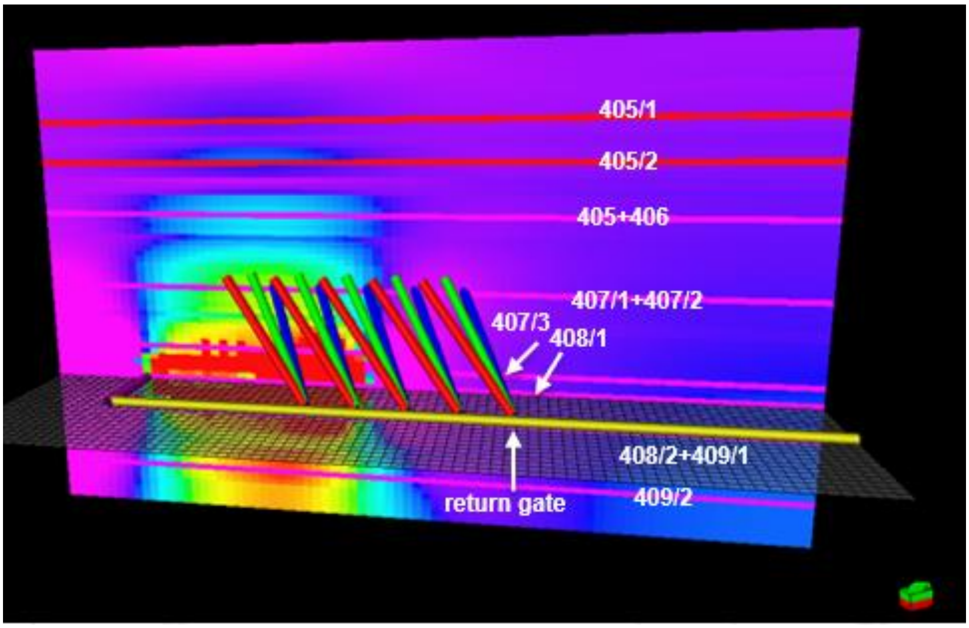


Figure 22.Jankowice colliery Z-11 longwall district methane drainage model targeting roof source seams

The relationship between the face position and drainage rate at each set of boreholes were investigated using the distance between borehole tips and the face line as the benchmark for performance. The model findings have suggested that the boreholes are most effective when they are in the highly stimulated permeability zone around 40-50 metres behind the face line. This finding is in agreement with the borehole probing data and the observations made at Jankowice in Task 3.1, where the highly permeability enhanced/fractured zone was determined as approximately 60 metres behind the faceline.

5.3. Conclusions from the numerical modelling of face emissions and methane drainage

Numerical modelling of face emissions at Coal Mine Velenje tracked the flow rates of gas migrating from the roof goaf, mining level and floor coal. The findings have suggested that the rate of gas emission from the mined coal is strongly affected by the coal face advance/retreat rate. However, floor coal and roof goaf act as a steady gas source accounting for a considerable part of the total gas emission.

These findings suggest that, in LTCC mining (and also in single slice longwalls) the emphasis on mine ventilation methane monitoring should be placed on the mined coal and gas emission from it being a lot more variable within a shorter timeframe, depending on the production parameters, such as the shearer movement and coal transport, and optimise the sensor locations accordingly.

On the other hand, methane drainage modelling has suggested that the maximum drainage rate from in seam and roof boreholes is reached when the face is within 10–12 meters from the borehole. It was also found that floor boreholes, although lover productivity compared to roof boreholes, will have a longer drainage life.

The Jankowice Colliery Z11 panel gas drainage model findings have confirmed that, as the face approaches the set of cross measure drainage boreholes, the drainage peak is encountered when the face line passes the borehole tips, and is approximately 40-50 metres behind them. This was found to be consistent with the findings of the borehole probing work in task 3.1.

6. OPTIMUM SENSOR LOCATIONS

Reviewing the work carried out in Work Packages 2 and 3 it was clear that combined efforts on systematic field monitoring of environmental conditions at longwall districts and numerical modelling of the same using mostly field base data increased our understanding of the processes behind methane emissions at the face and the flow paths of methane from sources outside the coal seam being mined.

The numerical modelling using CFD and/or coupled geomechanics and flow models produced results which are in agreement with field monitored data, and help understand the processes that lead to the observed emissions and gas concentrations.

The difference between the two longwall mining methods, single slice thin seam longwall and multi-level longwall top coal caving brings two fundamental differences in terms of the sources of gas emitted at the face. That is:

- In conventional thin seam longwalls up to 70-80% of the gas flowing towards the working district may be from the unmined seams above and below, with the mined seam contributing a relatively smaller percentage of the total emission budget. Which is why methane drainage is essential and plays a crucial role in maintaining safe working conditions.
- In the case of longwall top coal caving a much larger proportion of the gas emitted is sourced from the mined seam (including the top coal) and is not as practical to drain as a consequence.

- Nevertheless, in both cases, especially considering the much higher *in situ* gas content bituminous coals mined at greater depths as compared to relatively lower gas content lignites, the face emissions are high in volume flowrates and has to be controlled.

Another difference in the ventilation layouts observed between the two mine sites is the predominant use of Y-ventilation system in the Polish collieries and the U-ventilation system used at Coal Mien Velenje. This difference may, at times, introduce the need to place the methane sensors at different locations or increase the number of sensors used.

The so-called "short-Y" system discussed earlier and illustrated in Figure 23 may help provide significant amount of air to the face end at the tailgate but it also encourages high concentration of methane in a relatively small area and necessitate the use additional sensors.

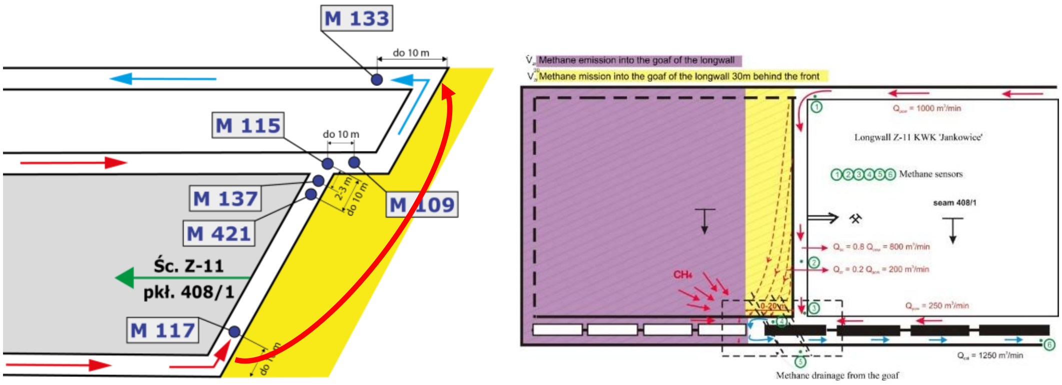


Figure 23. Different Y-ventilation layouts resulting in a similar "short-Y" ventilation conditions

On the other hand, U-type ventilation layouts may not always be able to provide sufficient air volume to dilute the methane emitted at high productivity coal faces. Therefore, in both cases, the control of production machinery in a system fed back from the methane sensors is essential, as demonstrated and developed in PICTO.

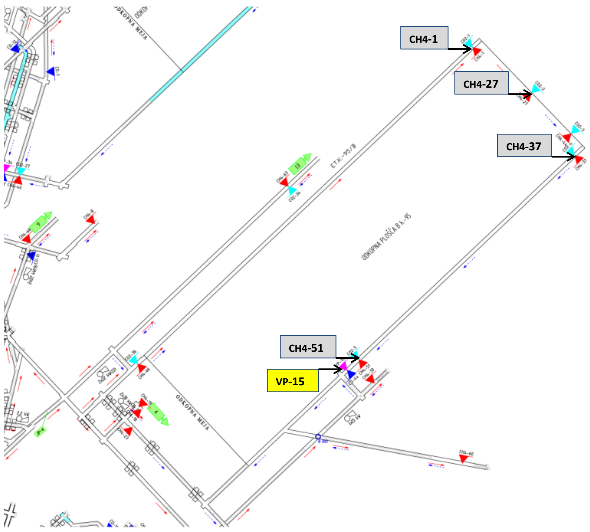


Figure 24. Methane sensor sites in a U-system Ventilation at Coal Mine Velenje

As Figure 23 and Figure 24 illustrate both Jankowice colliery and Coal Mine Velenje use sufficient number of sensors along the face. Monitoring data from the field has shown that these sensors tack the development and increase of methane concentration along the face from the main gate to the tailgate. On the other hand, current practice is to use only one sensor, and mostly one in the tailgate outside the production area itself, as the sensor controlling the power supply cut off to the face should the methane concentration at that point exceed the allowable limits. Such a system does not have the potential to react to rapid methane concentration peaks at the production face itself.

PICTO has developed and demonstrated that a close loop control system driven by a methane sensor and the prototype controller implemented on the VentGraph-Plus software can control the speed of the shearer. Review of all the findings in PICTO, rather than WPs 2 and 3 as originally planned, suggests that the next generation of this control system developed should use more than one methane sensor for this purpose.

The optimum number of methane monitors at the longwall face itself could be 3, placed strategically at the entry to the face, in the centre and at face end. As confirmed by the field measurements and CFD modelling, these should be as close to the roof as possible.

Together with the tailgate methane sensor, either in “U-system”, “short-Y” or “long-Y” ventilation layouts, these 3 longwall sensors can be operated in series, scanned by the shearer control system algorithm with some logic control in such a way that the shearer speed can react to methane peaks developing at the face, or those at the tailgate, depending on the conditions. This would help mitigate against increased methane concentration conditions often experienced towards the end of the production week, such as Fridays.

7. DATABASE FOR THE TIME-SPACE DEPENDENT DISTRIBUTION OF GAS CONCENTRATION AND DRAINAGE RATES IN RELATION TO PRODUCTION SCHEDULE AND MACHINE OPERATION STATE

Monitoring systems used in coal mines provide abundant information on the status of machines and ventilation air quality parameters in longwall headings and production faces. The data recorded in real-time and stored in databases of mine monitoring and supervision systems, independent of functions tracing the status of ventilation and changes in ventilation air quality parameters, enable their wide use and constitute highly valuable cognitive material. Attaining the project objectives of WP4 include the preparation of data from monitoring the operation of machines and methane emissions in longwall faces in real time, through their processing, cleansing and analysis of data. The data prepared in this manner allowed for the construction of a database, taking into account the temporal and spatial distribution of gas concentration in the longwall, as well as methane drainage parameters, depending on the production schedule and the operating status of the shearer. This task was aimed at the separation of useful data (data mining) from large files when monitoring the ventilation parameters of the longwall environment and, in particular methane concentration and methane drainage processes and the operating parameters of the machines. Selected fragments of the analysed data collected during the project have been used for modelling, validation of models and the testing of control algorithms, as well as the optimisation of the shearer operation in the methane hazard conditions.

Several state of the art big data analysis methods like data cleaning, filtering, smoothing, aggregation, exploration and mining have been applied.

This data has been organised in a database, taking into account the temporal and spatial distribution of gas concentration in the longwall, as well as methane drainage parameters, depending on the production schedule and the operating status of the shearer.

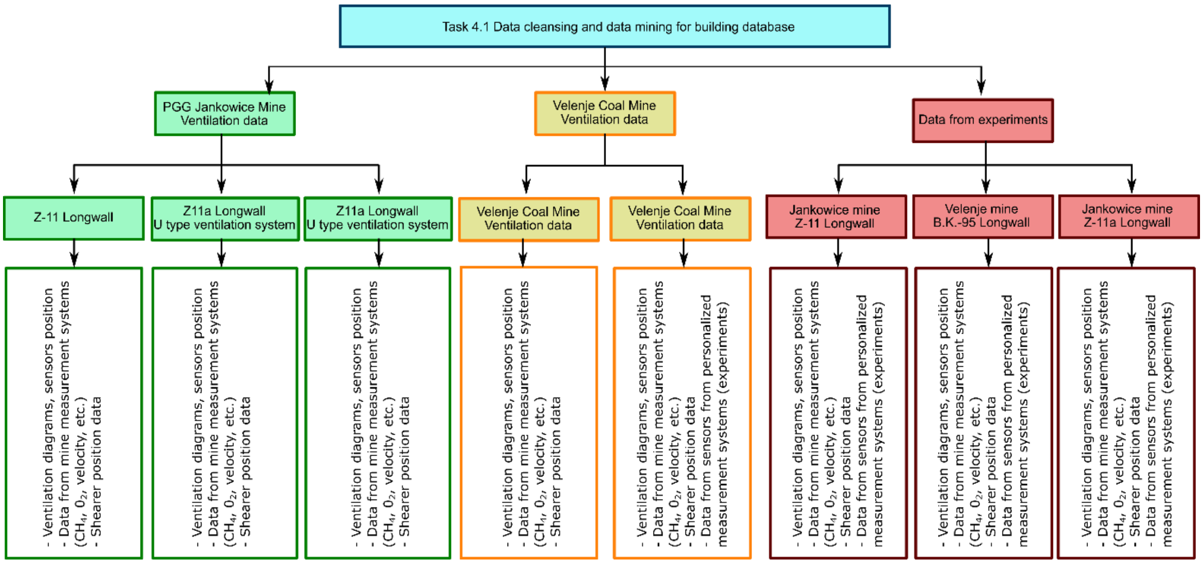


Figure 25. Layout of the database structure

The database includes the distribution of methane concentration and velocity profiles in the area of longwall Z-11 in a period from 1 February 2019 until 28 February 2019, and in the area of longwall Z-11a in period from 17 February 2020 until 22 June 2020 at Jankowice coal mine of the Polish Mining Group (PGG), as well as data on ventilation parameters in two longwalls B.k.-95 and D.k.-95 at CM Velenje lignite mine in Slovenia, in a period from 18 April 2019 until 26 April 2019. Additionally, the database is filled by ventilation, methane concentration, shearer performance and hourly coal production data acquired during field experiments conducted at longwall B.k.-95 on 16-18 June 2019.

The layout presented in Figure 25 shows a uniform configuration which includes mining and geological parameters, ventilation plan, location of sensors and data from monitoring systems belonging to methane safety and control system, including the records of methane concentration and air velocity, as well as the records of operating parameters of shearers and other equipment in the longwalls. The monitored ventilation parameters stored in the database also includes the records of methane drainage parameters in the Jankowice coal mine (PGG). Data stored have been supplemented with information containing description of the measurement area, sensors' location, experimental conditions, and many others details that are useful for data interpretation.

This **data repository has a potential of reuse** in the future analyses aimed at solution of the safety, economical and environmental protection problems with currently advancing data processing methods.

8. DEVELOPMENT OF CALIBRATED VIRTUAL MODELS OF THE LONGWALLS AND MULTIVARIATE SIMULATIONS FOR THE SELECTED PRODUCTION AREA

Actual field testing of the shearer control system must be preceded with a research, to be sure of its proper operation in an dangerous environment. Underground testing of the control system requires the necessary ATEX certification and length approvals through the relevant national authorities in each country. Getting such approvals is not possible within the three years project duration. That is why PICTO is a precompetitive Research and Technological Development project, rather than a Demonstration/Pilot project. In PICTO the control system has been developed and tested on so called Virtual Longwall Models.

The Virtual Longwall Models may be considered as a kind of a digital twin of the district on an underground mine. Those models are a variant of the Ventgraph Mine Ventilation Network Computer Simulator. A calibration of this simulator upon a field data has guaranteed the twins identity. Then most of the real mine testing may be replaced with experimening on its digital twin.

Current chapter outlines the calibration precess, which has provided a credible digital representation of both classic single slice and thick seam top coal caving longwalls.

During Virtual Longwall Models development the VentGraph-Plus program has been modernised by adding new procedures customized to the PICTO project needs. They provided improved ways of simulating the work of the shearer in the longwall and the haulage of the produced coall, taking into account the balance of methane emitted during production.

Based on the adopted mathematical models, for a longwall with a working shearer, the equations of methane emission from the fracture zone in front of the shearer and from the exposed coal face behind the shearer were adopted, and the equations of methane emission from the excavated coal on the Armoured Face Conveyor (AFC) and belt conveyor in the gateroad were taken into account.

In order to conduct further research to determine how methane concentration changes during production methodes applied so far and forecasting the effect of the regulation of the shearer operation, Virtual Longwall Models were developed for selected longwall districts:

- the area of longwall 841A, seam 405/2, U ventilation system, Bielszowice Colliery, Poland,
- the area of longwall B k. -95, U ventilation system, Coal Mine Velenje, Slovenia,
- the area of longwall Z-11a, seam 408, Y ventilation system, Jankowice Colliery, Poland,
- the area of longwall Z-11a, seam 408, U ventilation system, Jankowice Colliery, Poland
- Their main elements of the numerical model were:
- ventilation system of the longwall district,
- the adjacent goafs,
- operation of the shearer,
- operation of the shearer speed controller, activated during controlled operation,

- the methane balance, including the inflow of methane from freshly won coal mass and from the coal transported on conveyors; the inflow of methane from the goafs of the mined seam, the seams lying above and below, as well as taking into account methane drainage by the drainage boreholes (if present).

Following paragraphs and figures outline some stages and results of the calibarion on examples of the C.M. Velenje B k. -95 Z11a Jankowice coliery longwalls.

The first model, representative for the district of longwall 841A, was used as a test case for the validation of the applied new mathematical models of the newly developed ***VentGraph-plus*** software and in the calibration methodology, in particular identification of numerical model parameters for the selected area. This case used a historical data of three 5-th October 2009 high energy rock bursts causing pressure, airflow velocity and methane concentrations disturbances. Records of this event paried with the records of a normal shearer operation provided an uniqued dataset.

After sucessfull calibration for the longwall 841A test case, the ***VentGraph-plus*** model could be considered as sufficiently accurate for both the event and normal operation, which justifies application of such models for the Workrk Package 5 forecasting of the effects of the shearer control. After such confirmation of the model validity, models of the Z11a and B k. -95 longwalls invesitgated within the projetct have been calibrated.

Results of their calibration have been more extensively described in the deliverable D4.3, which also presents the general methodology of the development of the numerical models on the examples listed above.

8.1. Numerical model of the longwall district Bk-95

Data on the estimation of methane inflow to the B k. -95 longwall district during mining, the average amount flowing through the longwall, elevations, the geometry of the excavations in the longwall district, mine surface area, the number of mining layers (counting from the top), the cutting drum web, average speed of the shearer, and average height of the mined coal was also obtained from the engineers at the mine.

The B k. -95 longwall was ventilated using U ventilation system combined with an auxiliary ventilation system, which supplied 234 m^3/ min of additional fresh air to the longwall face out bye end. A ventilation diagram of the longwall district is shown in Figure 26.

To determine the parameters of the numerical model of the goafs of the Bk-95 longwall, the data and the 3D model presented in the Deliverable D3.3 was used. After analysing the available data, the geometry of the goaf and its properties like distributions of prosity and permeability have been determined.

The data characterising the air and methane mixture flow in excavations were based on available measurement data taken in the area of the Bk-95 longwall and on the basis of an analysis of the numerical model of the longwall developed by Coal Mine Velenje using Ventsim software (i.e. flow rates and ressistances). Data recorded by methane sensors and stationary anemometers of the monitoring system, as well as the results of measurements on 16 June by the SOM-2303 methane anemometer system, were used to determine the initial flow of the air-methane mixture for the numerical model of the longwall, longwall workings, and goafs.

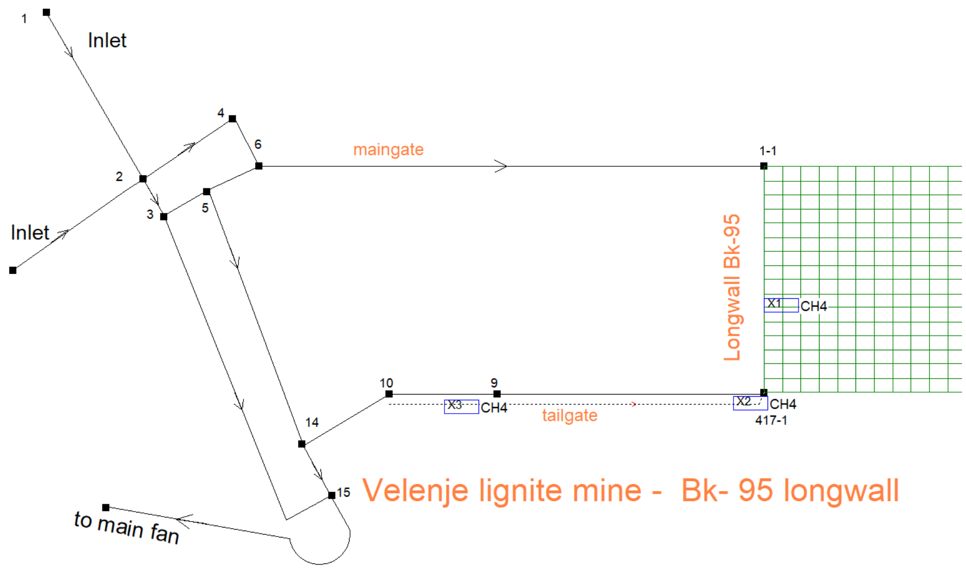


Figure 26. Numerical model, ventilation scheme of the B k. -95 longwall district with grids of goaf branches; dashed line - auxiliary ventilation, X1 CH4 - methane sensors of the monitoring system

Records of changes in methane concentrations before and during shearer operation at the Bk-95 longwall and goafs allowed us to determine the balance of the volumetric flow of methane contained in the longwall and at the inlet and outlet of the longwall, and methane flowing to the goaf area. The total methane inflow of 13.14 m^3CH_4/ min was determined using the CH4_51 sensor. According to the CH4_01 sensor measurements at the wall inlet the methane concentration was 0.06% CH_4, which for the air flow rate to the longwall of 1818 m^3/ min gives the methane flow rate at the inlet equal to 1.09 m^3CH_4/ min.

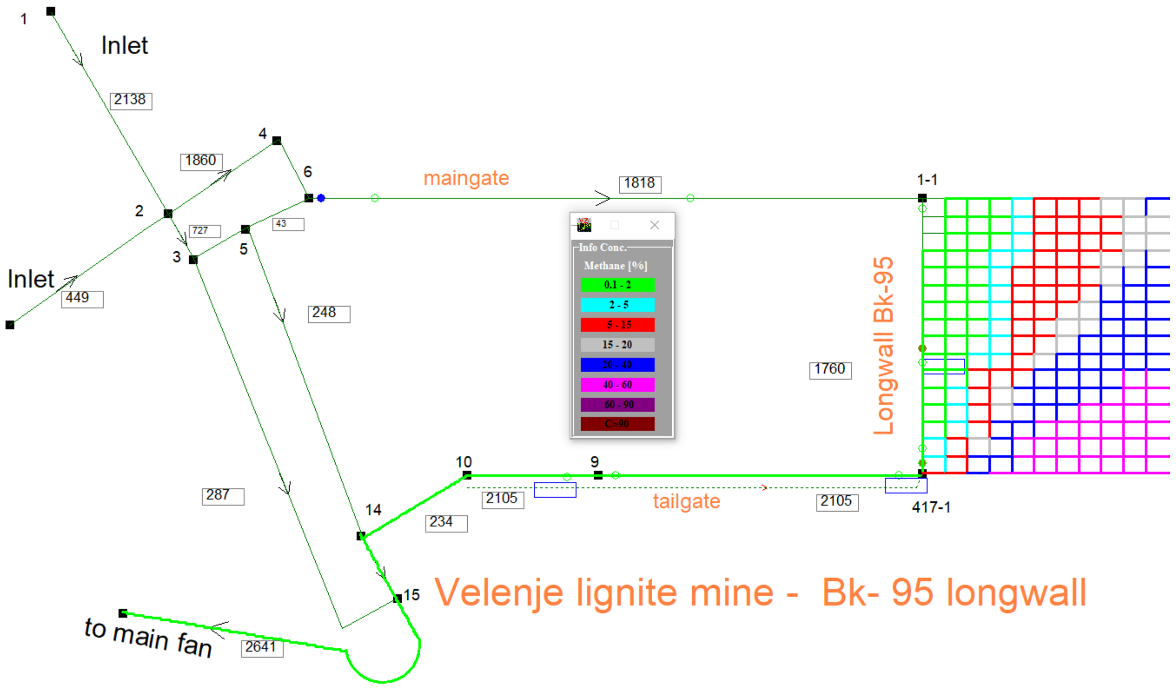


Figure 27. A ventilation scheme of the B k. -95 longwall district with grids of goaf branches, coloured bold lines – distribution of methane concentration in longwall goafs, - rectangles show the air flow volume stream (m3/min); arrows show the direction of flow; numbers at junctions highlight their identification

According to the calculations carried out in ***VentGraph-plus*** software for the developed numerical model, the initial flow rate of air and methane on June 16 from 12:30 pm to 1:20 pm was as follows:

- the volumetric air flow rate at the end of the wall was 1,818 m3/ min, according to measurements the average flow rate the wall was 1,728 m3/ min,
- the volumetric air flow rate in the tailgate was 2,105 m3/min, including additional 234 m3/min supplied by an auxiliary ventilation system.
- the methane concentration at the location of No. 51 sensor (CH4_51) was 0.48 %.

This data has been used to build a numerical model of the longwall district with the Ventgraph software and obtain solutions of the flows and gas concentrations in in its branches. Figure 27 shows an example of a solution for the initial state of air and methane distribution in the workings of the area and goafs. The colour scale shows the distribution of methane concentration in the goaf, and the rectangles show the amount of air flowing through.

8.2. Calibration of the numerical model for data as of June 17, 2019

Achieving the credibility of the simulation results using ***VentGraph-plus*** software requires its calibration, which consists in comparing methane concentrations recorded during the measurement experiment at selected points of the longwall and adjacent workings with changes in methane concentrations obtained as a result of computer simulation for the same points of the computer-modelled region.

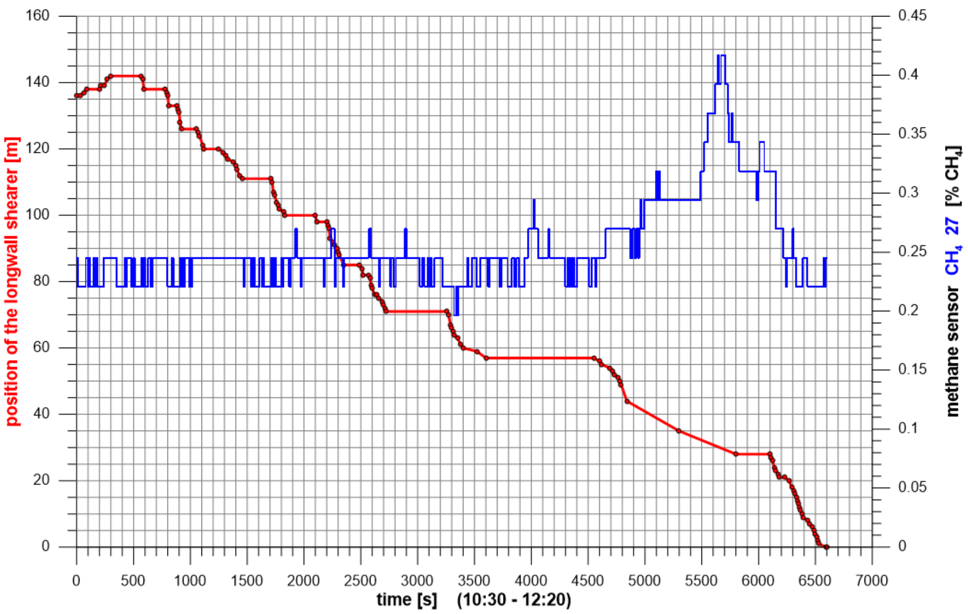


Figure 28. Longwall shearer operation as a function of time - red line, methane concentration changes for sensor CH4_27 - blue line

Calibration of the numerical model developed with ***VentGraph-plus*** software was performed using data from the *"in situ"* monitoring system from Coal Mine Velenje for the B k. -95 longwall face on June 17, 2019. from 10:30 am to 12:20 pm. Variant simulation calculations of the unsteady state caused by the shearer operation were carried out. The simulation was performed using the developed operation schedule of the shearer. During subsequent calculations, selected parameters characterising the air flow, including methane inflow and data describing the shearer operating parameters, were changed. The aim of the research was to change the selected model parameters in such a way as to minimise the distance between the time series of methane concentrations measured and obtained by numerical modelling.

Based on the Figure 28, the shearer operation schedule was developed using the data on the position of the shearer as a function of cutting time, the current speed of the shearer was calculated, and the result was presented as a numerical set, which served as the input data for the simulation using VentGraph-Plus software. The developed schedule is shown with the red line in Figure 28, the blue line shows the changes in methane concentration measured by the methane sensor No. 27 located in the B k. -95 longwall face.

Figure 29 shows the VentGraph-plus software control panel, which shows longwall shearer operation (+1), shearer standstill (0) and cutting against the air flow (-1); the red line shows the shearer speed.

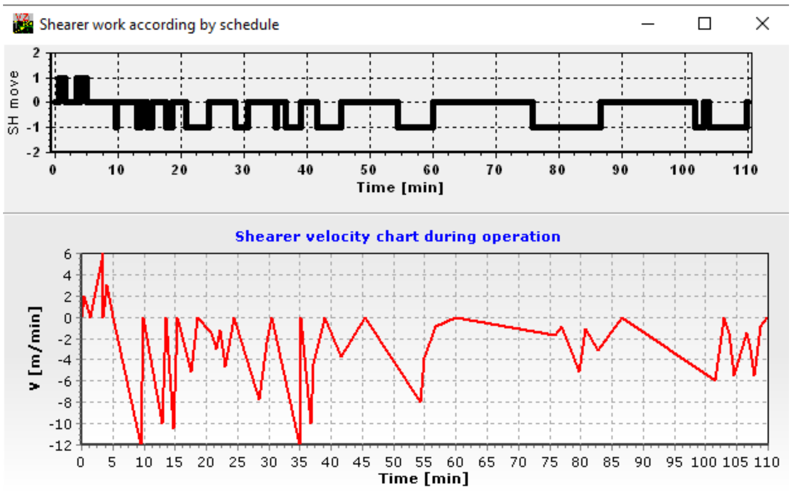


Figure 29. Changes in the shearer's cutting speed as a function of time - red line, shearer operation in the longwall: 1- cutting towards the longwall outlet, 0-standstill, -1 cutting towards the inlet against the air flow - black line

The main features of the schedule (Figure 28, Figure 29) are:

- variable speed of the shearer during cutting in the selected direction,
- standstills of the shearer,
- changes in cutting direction,
- changes in the distance travelled between shearer operation and standstill.

The shearer moves in the B k. -95 longwall according to the presented schedule (Figure 28); while mining the coal, it reveals the surface from which methane is desorbed. The haulage of the output takes place in the opposite direction to the air flow.

In oreder to properly assess the effect of the shearer on the environmental conditions at longwall several paremeters had to be determined. They can be divided in two groups.

The first one contains the parameters of the longwall, which include: local moving aerodynamic drag resulting from the dimensions of the shearer, face height, coal density, shearer cut depth, initial cutting speed of the shearer, speed of excavated material (output) transport on the AFC conveyor and belt conveyor in the gate road.

The second group of data are the model parameters for methane emissions from the unmined coal and excavated material transported by conveyor belts.

In the model calibration calculations, particular attention was paid to the course of methane concentration measured by the sensor CH4-27 located in the middle of the longwall (the sensor for which the calibration was performed). The results of the computer calculations are presented in graphs of changes in methane concentration measured by virtual sensors of VentGraph-Plus software and based on the values measured by the mine monitoring system. Figure 30 to Figure 32 show the predicted (dashed orange line) and recorded (using the sensors of the monitoring system) (solid black line) methane concentrations.

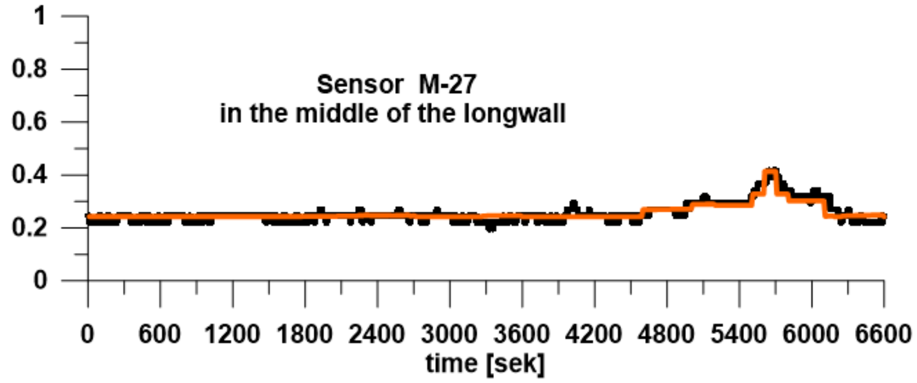


Figure 30. Changes in methane concentration in the middle of the longwall, sensor CH4-27, orange line – simulation, black line - monitoring

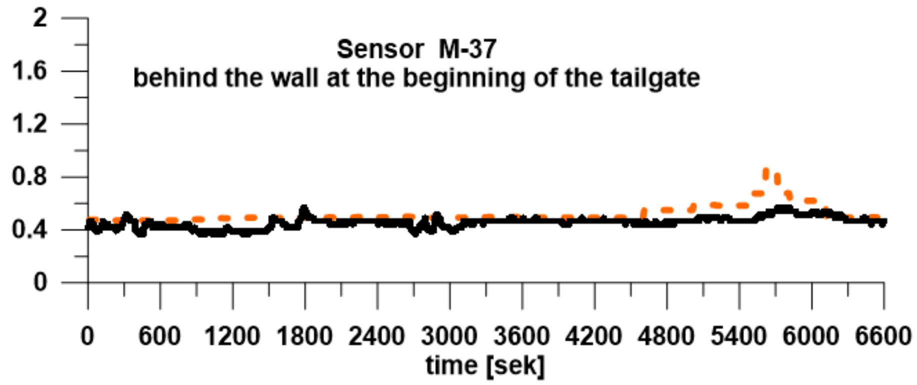


Figure 31. Changes in methane concentration 10 m from the longwall outlet, sensor CH4-37, orange line – simulation, black line – monitoring

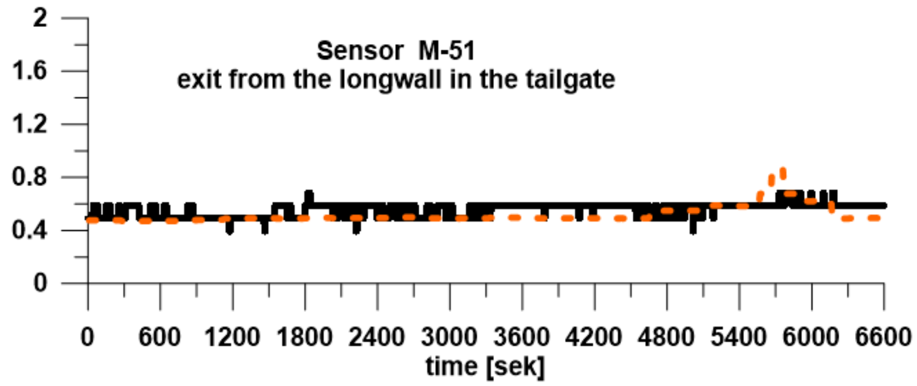


Figure 32. Changes in methane concentration in the tailgate, 80 m from the longwall outlet, sensor CH_4-51, orange line – simulation, black line - monitoring

The time series of changes in methane concentration recorded by the sensors of the monitoring system, presented in Fig. 37 to 39, show significant variability especially in the longwall and in the tailgate discharging air from the longwall. Particularly good representation was obtained for the sensor No. 27. For sensors No. 37 and 51 located in the tailgate that discharges air and methane from the longwall, a certain difference was obtained, especially in the final phase of the simulation, in the period from 5,400 seconds to 5,650 seconds. It is difficult to clearly explain the observed increase in methane concentration resulting from simulation compared to sensor measurement. This leads to the observation that there are strong flow fluctuations and rapid mixing of air and methane in the area of sensor No. 37, and that the simulation calculations carried out do not take this mixing pattern into account.

The obtained results of model calibration allow us to state that the parameters of the numerical model were properly selected, and the applied mathematical models correctly reflect (simulate) the actual situation. The methane concentrations measured by subsequent methane sensors, resulting from changes in flow conditions during the cutting with the shearer, showed good qualitative agreement with those simulated using ***VentGraph-Plus*** software.

8.3. Calibration of the Z11A longwall numerical model

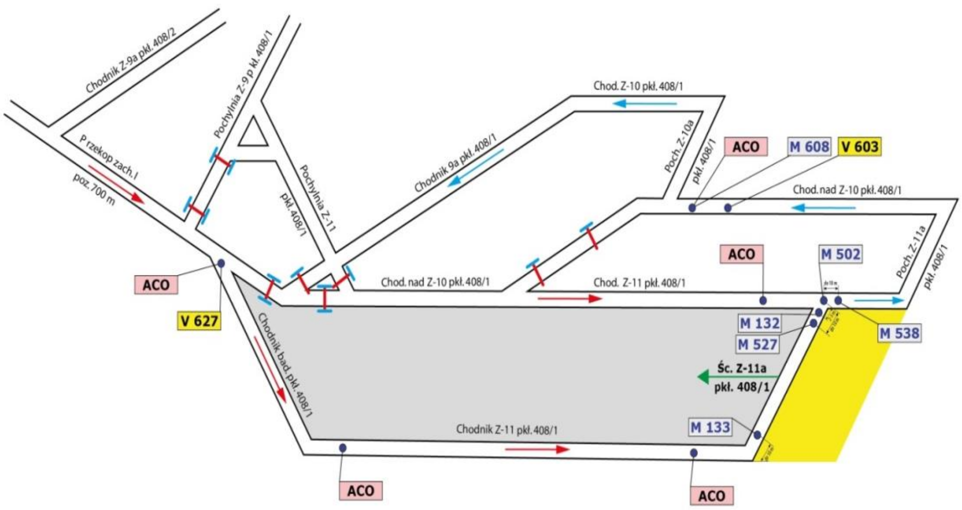


Figure 33. Scheme of the Z-11A longwall in seam 408/1 with the monitoring system sensors

Calibration of the numerical model developed was performed using data from the *"in situ"* monitoring system from the Jankowice mine for Z-11A longwall on 17.06.2019 from 10:30 am to 12:20 pm. Variant simulation calculations of the transients caused by the shearer operation were carried out. The simulation was performed using the developed operation schedule of the shearer.

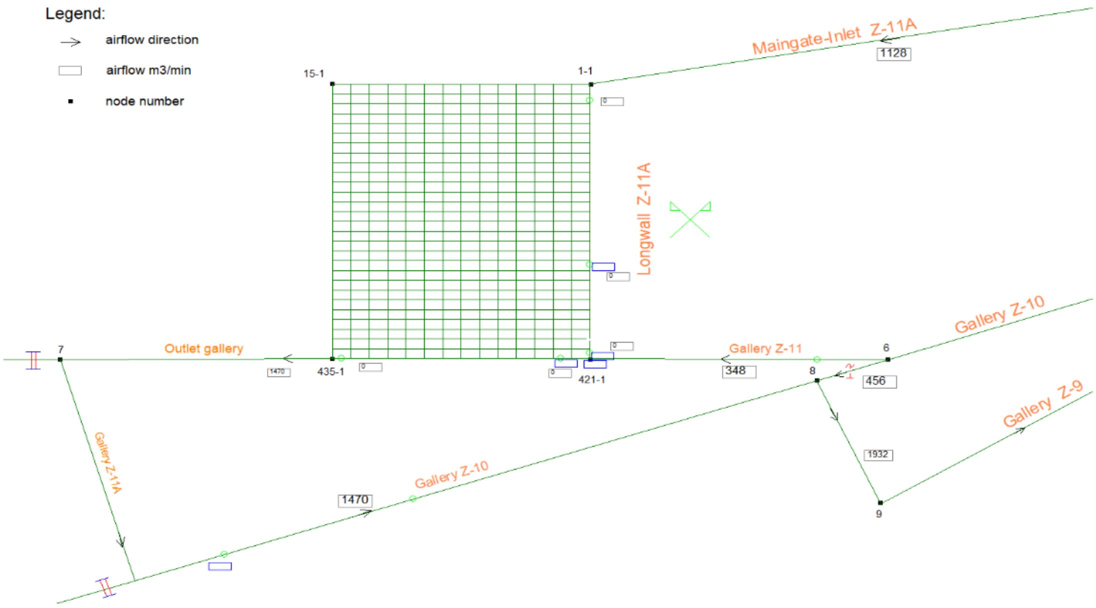


Figure 34. Numerical model of the Z-11a longwall district with grids of goaf branches in rectangles showing the air flow volume stream (m^3/ min), with arrows showing the direction of flow and numbers at junctions highlighting their identification

During subsequent calculations, selected parameters characterizing the air flow, including methane inflow distribution along the longwall and data describing the shearer operating parameters, were changed. During the process of calibration, those parameters were modified within acceptable limits (i.e. measurement uncertainty) in such a way as to minimise the distance between the time series of methane concentrations measured and obtained by numerical modelling.

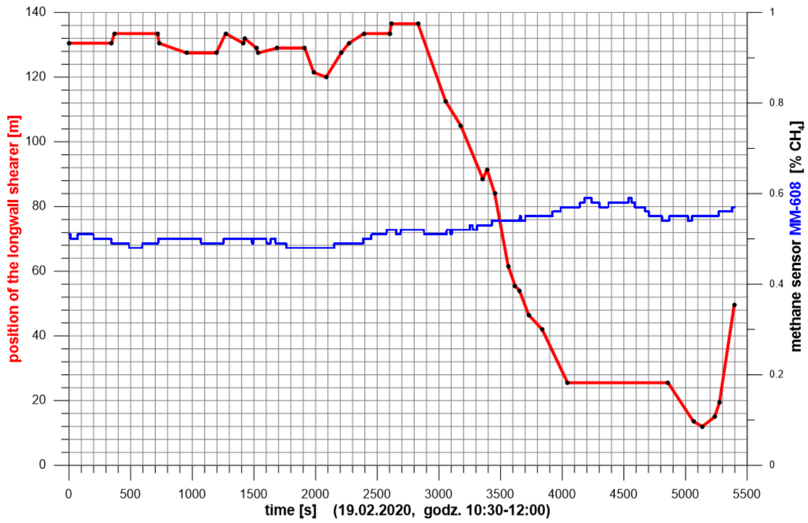


Figure 35. Longwall shearer operation as a function of time - red line, methane concentration changes for the MM-608n sensor - blue line

Based on the monitoring records, the shearer operation schedule was developed using the data on the position of the shearer as a function of cutting time, the current speed of the shearer was calculated, and the result was presented as a numerical set, which served as the input data for the simulation using VentGraph-Plus software (Figure 34). The developed schedule is shown with the red line in Figure 35, the blue line shows the course of changes in methane concentration measured by the MM-608 methane sensor located in the Z-10 longwall.

Figure 36 shows the VentGraph-plus software control panel, which shows longwall shearer operation (+1), shearer standstill (0) and cutting against the air flow (-1); the red line shows the shearer speed.

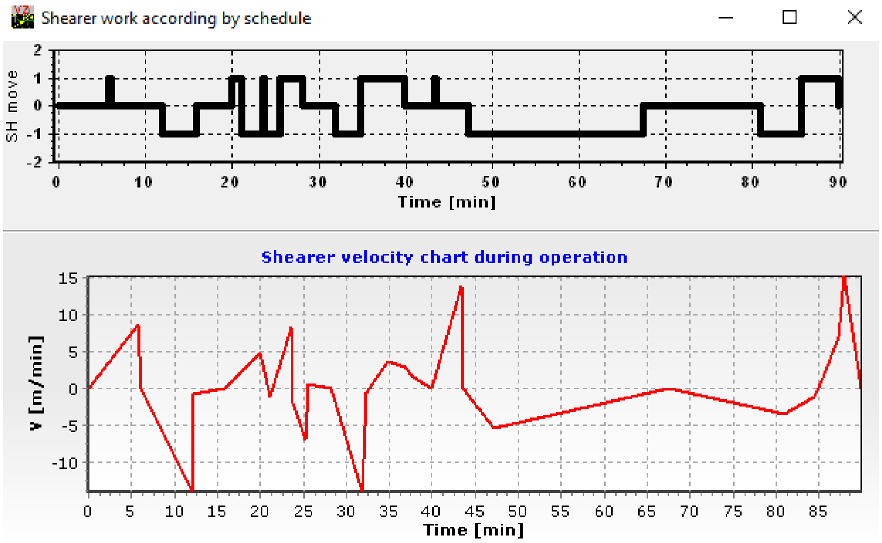


Figure 36. Changes in the shearer's cutting speed as a function of time - red line, shearer operation in the longwall: 1- cutting towards the longwall outlet, 0-standstill, -1 cutting towards the inlet against the air flow - black line

The shearer moves in the Z-11A longwall according to the presented schedule (Figure 35).

For so developed model a number of multi-variant simulations were performed in order to calibrate and verify the accuracy of the model for the predetermined work schedule of the shearer in the longwall. Objects (four regions) were calibrated by determining such values of the mathematical model parameters at which the output signals of the model are as close as possible to the output signals of the real object for the same input signals.

In particular the actual records of the monitoring system have been compared with the simulation results. The following figures from Figure 37 to Figure 38 show the predicted (dashed orange line) and recorded (using the sensors of the monitoring system) (solid black line) methane concentrations. The sensors location has been shown in the Figure 33.

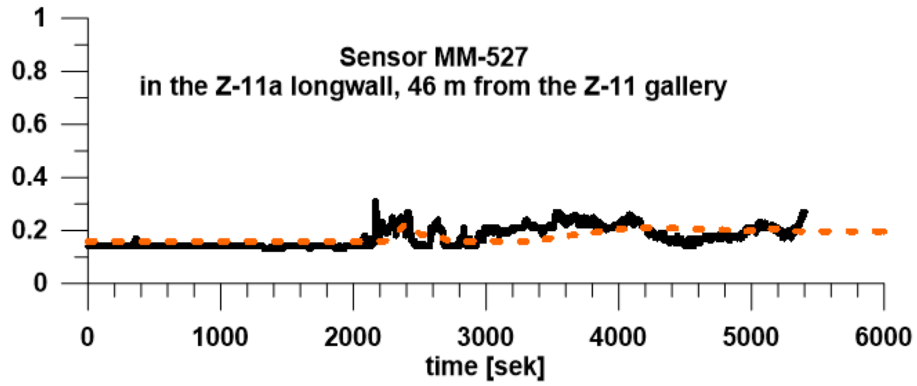


Figure 37. Changes in methane concentration 46 m from the longwall outlet, MM-527 sensor orange line – simulation black line - longwall monitoring

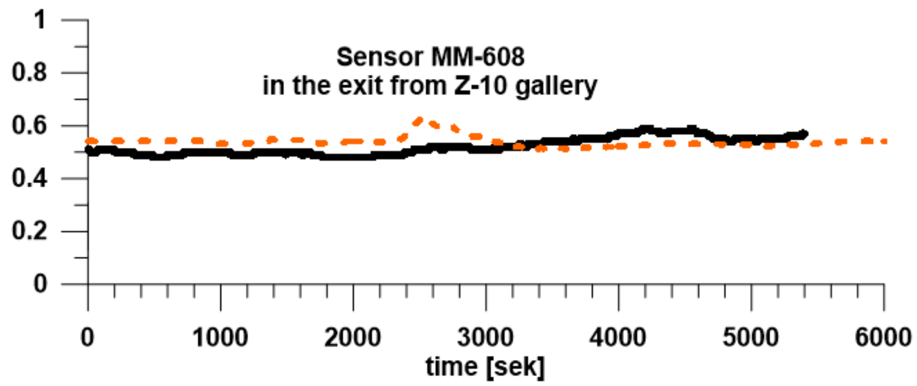


Figure 38. Changes in methane concentration at the inlet of the Z-10 gallery, MM-608 sensor, orange line – simulation, black line - longwall monitoring

Validation of the mathematical model used in the software and calibration of the numerical models indicated good consistency of calculation procedures used in the computational algorithms, and it confirmed the practical application of this model in programs for numerical modelling of ventilation networks in mines with consideration of goafs presence.

Because of the presented results of comparisons between the trends of methane concentrations and air flow rates, as recorded by the mine monitoring system, field experiments results and opinions of relevant mine operators representatives and researchers from institutions involved in this task it can be concluded that the changes in speed and methane concentration over time for the longwall district have been successfully recreated, proving that the adopted mathematical models and algorithms are correct and applicable for the Optimal Control Demonstrator's shearer control system development and testing.

9. DEVELOPMENT OF PROTOTYPE OF PRODUCTION UNIT CONTROL ALGORITHMS AND PROCEDURES

There is a known relationship between the methane concentration in the air stream flowing from the longwall and the intensity of mining, i.e. the stream of mined coal, which depends in turn on the shearer's movement speed and depth of pull as well as the cutting height (Krause, 2009). It is possible to state that the methane concentration in this air stream increases with the growing output. The exceeding of a 2% methane concentration threshold – measured by means of methanometers within the mine gas measuring system, which are situated in the air stream at the longwall and in the roadway discharging the air from the longwall – results in switching off the equipment supply voltage in the longwall area and a production downtime.

The task of maintaining the methane concentration below 2%, that is, the task of controlling, is carried out by a closed control system, i.e. a system of automated control with a feedback loop. In this system the controlled object consists of the area of the mined longwall, a shearer with a regulated cutting speed, an armoured face conveyor (AFC), a conveyor in the haulage road, and methanometers of the mine gas measuring system (Figure 39). This chapter outlines the main features of this control system. More information can be found in the paper of Dziurzyński et al. (2018).

Inputs, including control signal and interference, affect the controlled object. The speed of the cutting shearer is the control signal because, as mentioned above, the stream of output depends on this speed. Methane is released from the output, transported by the AFC and the haulage conveyor, to the stream of air ventilating the longwall area. In addition, increased methane release from the longwall solid in the vicinity of the shearer is related to cutting. The signal from the methanometer placed at the longwall outlet, proportional to the measured methane concentration, is the process variable (PV). It is single-input-single-output system (SISO). If a few methanometers are situated at the longwall, there are a few outputs. In addition, the PV is affected by interference signals, both measurable and immeasurable. Measurable interference signals comprise the speed of air inflowing to the longwall as well as the methane concentration in this air, as measured by an anemometer and a methanometer (in Figure 39, anemometer A and methanometer M). Immeasurable interfering signals include unplanned shearer stops, random components of methane release from the longwall solid, methane inflow from the goaf, and methane inflow from the mined coal on conveyors.

The controlled object transforms the input into output. To determine the relationships between the input and output signals, it is necessary to identify the controlled object, i.e. develop its mathematical model. A mathematical model of the object describes relationships between the output signal, that is, the signal proportional to the methane concentration measured by a methanometer situated in the air stream flowing from the longwall (methanometer M0 in Figure 39), and the control signal, which is the shearer cutting speed and interference signals. The number of output signals may be larger than one if additional methanometers are installed at the longwall (methanometers M1 and M2 in Figure 39). The shearer cutting speed is directly related to the distribution of methane inflow from the longwall coal solid and from the output on conveyors. The shearer cutting speed is a product of shearer movement speed and the index of cutting, which is 1 when the shearer is cutting and 0 when it is not cutting.

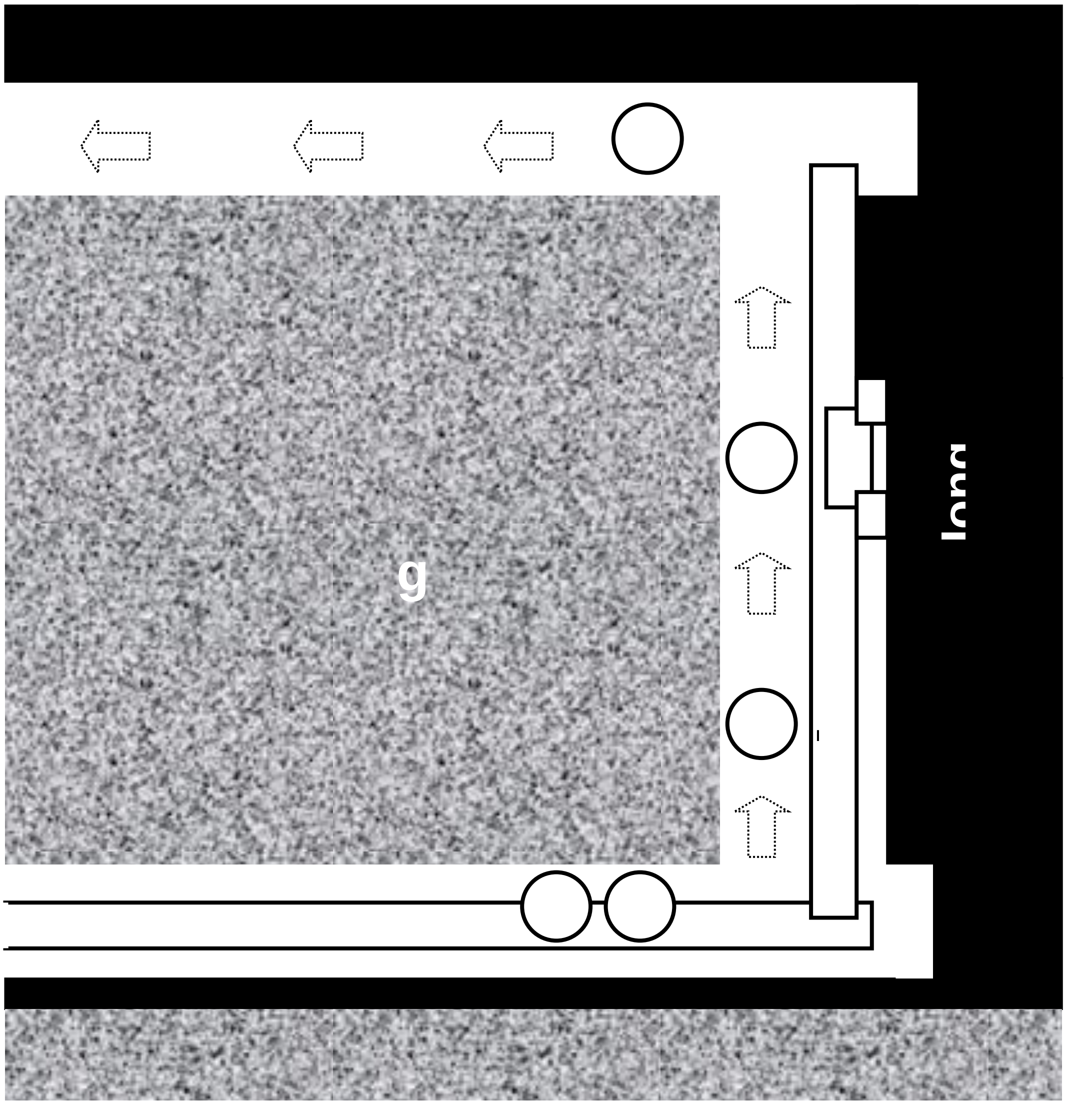


Figure 39. Controlled object: The area of longwall with a cutting shearer.

K - shearer. PS - armoured face conveyor. PO - haulage conveyor. A - anemometer. M - methanometer at the longwall inlet. M0 - methanometer at the longwall outlet. M1, M2 - additional methanometers at the longwall

The mathematical model of the longwall area with the shearer consists of the following models: a model of methane emission from the coal mass undergoing winning, a model of methane emission from the extracted rock on the longwall and haulage conveyor, a model of goafs adjacent to the longwall face, a model of methane distribution in the ventilation network of the mine, and a model of methane monitoring. The model of goafs and the model of methane distribution are components of the *VentGraph Plus* software.

In the longwall model, it was necessary to take into account the variable moving speed of the shearer, with periods of winning and times of stoppage, and the distribution of methane flow rate out of the undisturbed longwall that is related to winning. In the model of methane emission from coal on the longwall and haulage conveyor, the primary issue is the distribution of linear density of the volumetric flow rate of methane (flow from a unit length) from coal in time and space, on the longwall conveyor and on the haulage gate road conveyor. This model has been presented by Dziurzyński et al in year 2019. The mathematical model of the longwall area provides a basis for generating a numerical model of the area, which, after implementation in the *VentGraph Plus* software, allows for simulating the operation of the shearer in the longwall, additionally taking into account methane flowing to the longwall from goafs and from over- and underlying seams, along with simulation of the distribution of methane in the ventilation network of the mine.

The objective of control, which is maintaining methane concentration in the longwall below the value of 2%, is intended to be achieved by an automatic regulation system with a closed feedback loop. **Figure 40** presents the diagram of the control system. Methane concentration in the air current flowing out of the longwall is measured using a methanometer with a function of deactivating power supply voltage in the longwall area in the event of exceeding the 2% level in the measured methane concentration. Hence, the input value of methane concentration provided to the summing node of the controller must be lower than 2%. The error signal from the summing node is processed in the PID controller and, after transformation in the control system into the shearer speed signal, it is transmitted to the shearer operator’s readout panel, or directly to the control system of the shearer.

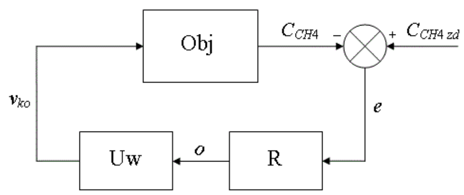


Figure 40. The control system of methane concentration at the outlet of longwall mined by a shearer.

Symbols in the figure:

Obj - controlled object: shearer mining coal in the longwall, with methane flowing from the mined seam, from the adjacent goaf, from the output on the armoured face conveyor, and on the conveyor in the haulage road, and with methanometers measuring the methane concentration in the air stream at the longwall outlet.

R - controller,

Uw - output system,

C_{CH4} - measured methane concentration, process variable (PV),

$C_{CH4\ zd}$ - preset methane concentration, setpoint (SP)

e - error signal SP - PV,

o - output signal of the controller,

v_{ko} - calculated speed of shearer movement.

This is a control system with a fixed setpoint $C_{CH4\ zd}$ < 2 %.

Since the methane content of a coal seam can change along with the advancement of the longwall, the distribution in time and space (along the longwall) of methane emission rate from the rock mass being excavated can change as well. In order to improve the quality of regulation, an **adaptive system of regulation** has been adopted, where multi-point measurement of methane concentration has been used, due to the variable distribution of methane concentration along the longwall, resulting from the movement of the winning shearer. Control is taken over by consecutive sensors of methane concentration, distributed along the longwall. Two versions of the calculation system have been proposed:

a) signals from the methanometers are transmitted to the system having the highest value of input signal at the output, and this signal is transmitted to the input of the PD controller.
b) each of the input signals is transmitted to the input of a separate PD controller, and only signals from the output systems in the calculation system are transmitted to the system having the minimum value of input signals of this system.

The generation of numerical algorithms for the operation of the methanometer and the PID controller with a summing node and an output system has been tested on the Virtual Longwall Models, being a kind of digital twins of the longwalls representative for both mining methods considered by the project. Following chapters present estimation of the advantages of proposed control system.

10. TEST BENCH FOR CONTROLLED SHEARER OPERATION

Before eventual field testing, the shearer control system must be throughly verified. Much of this testing may be done in laboratory conditions by connecting the Virtual Longwall Model with the shearer’s hardware and software. Such set may be used for testing the control system in safe environment and without a need of use of a whole shearer. Due to a special arrangement of auxiliary software and cabling the shearer control hardware and software fuction as if it they have been placed in a shearer.

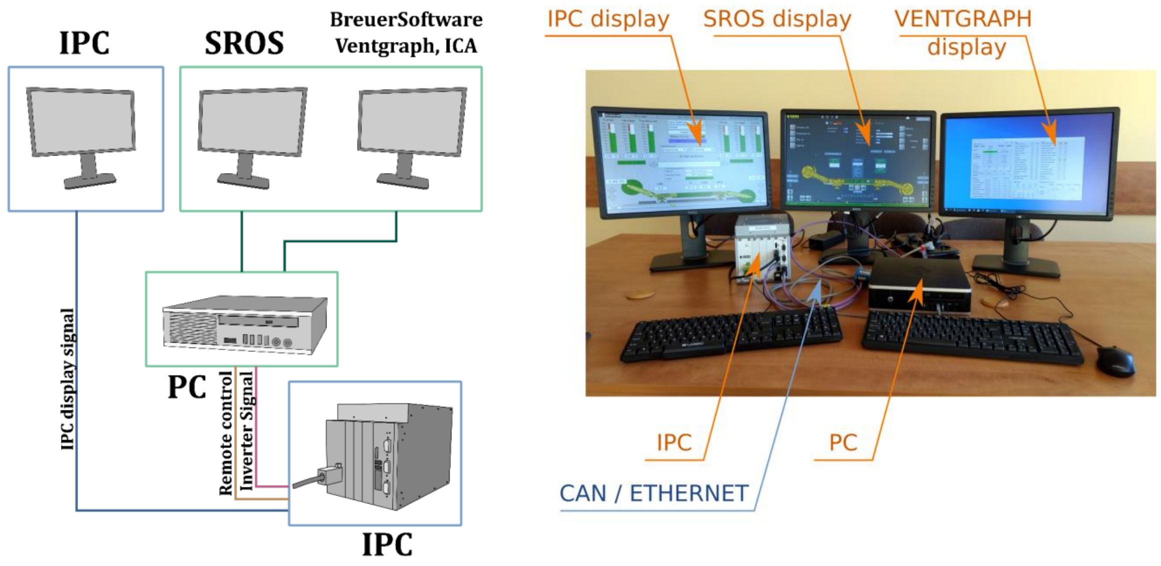


Figure 41. Shearer control system – Production Unit Control. IPC (Industrial Power Computer), SROS – enables remote control by the operator, PC allows to computer virtual longwall’s model.

The Virtual Longwall Model is based on the version of the VentGraph-Plus Mine Ventilation Network Simulator, customized to the needs of the Project. The procedures of the target control system have been embedded in this software. The simulator uses models of longwall districts, which have been calibrated to ensure realistic conditions. The simulation system provides a possibility of remote control from a surface or a distant safe place underground. The system can work automatically using a virtual sensor corresponding with the longwall's model. In future implementation the virtual sensor will be replaced by a real sensor. This solution guarantees that a later implementation on a real shearer loader can be done without additional software changes and allows a very realistic simulation with the VentGraph-Plus software.

In order to give the **Optimal Control Demonstrator** the ability to affect the machine speed, special functionalities had to be implemented in the shearer software. Upon the Virtual sensor indications, the contoller calculates the maximum value of cutting speed, at which the longwall atmosphere remains within the safety limits with regard to the methane hazard. This value is sent via the Modbus/TCP interface to the shearer internal control system. The shearer's IPC contol system may set a smaller value due to the other control algorythms implemented into the shearer software to ensure the safe operation of the shearer loader. For practical reasons the demands of the VentGraph-Plus system and other control inputs have to be taken into account and processed at the same time. Each 100 ms the VentGraph-Plus sends a Modbus frame that updates a safety counter. This counter is responsible for continuous shearer operation. If the shearer did not receive the frame and did not update the counter, the connection will be broken and the shearer will stop.

As the actual cutting speed may be different than the preset one, the simulator must communicate with the shearer to get its actual state and update the Virtual Model accrodingly.

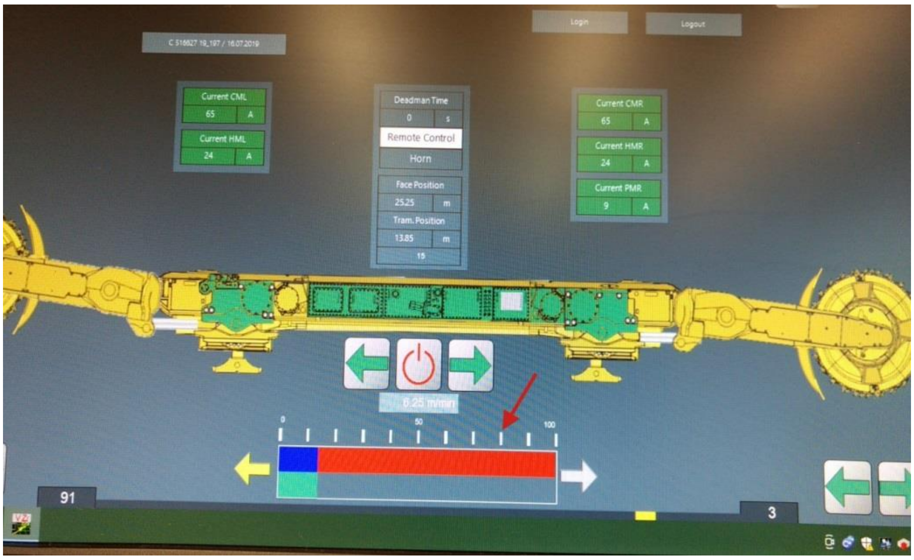
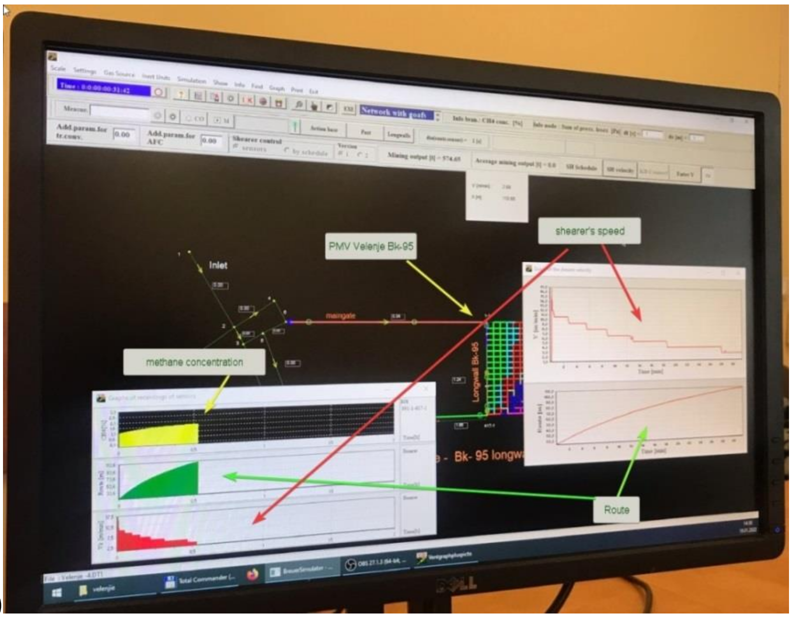


Figure 42. SROS software receives speed limitation from VentGraph-Plus

On the test bench the shearer IPC is close to the standard PC with the VentGraph-Plus system on. In a real longwall application there will be a greater distance between these two devices. As the communication is based on TCP/IP the greater distance will not influence the communication. In VentGraph-Plus software we should set proper IP number for shearer IPC to connect them.

VentGraph-Plus has a plug-in that was coded during the project that can connect to the shearer via TCP/IP socket. Choosing “shearer Eickhoff” in simulation preferences we decide to set the real shearer instead of a numerical model of the shearer. Longwall’s environment like methane concentrations, methane emission, air velocity are being simulated by the model. After start the of the VentGraph-Plus simulation the shearer receives speed limitation (the red bar at Figure 42). The shearer slows down to keep right speed to mainatin a safe level of the methane concentration. Any simulation parameters like the shearer’s speed, position, route, methane concentration can be observed during the simulation and saved to data files.

a) 

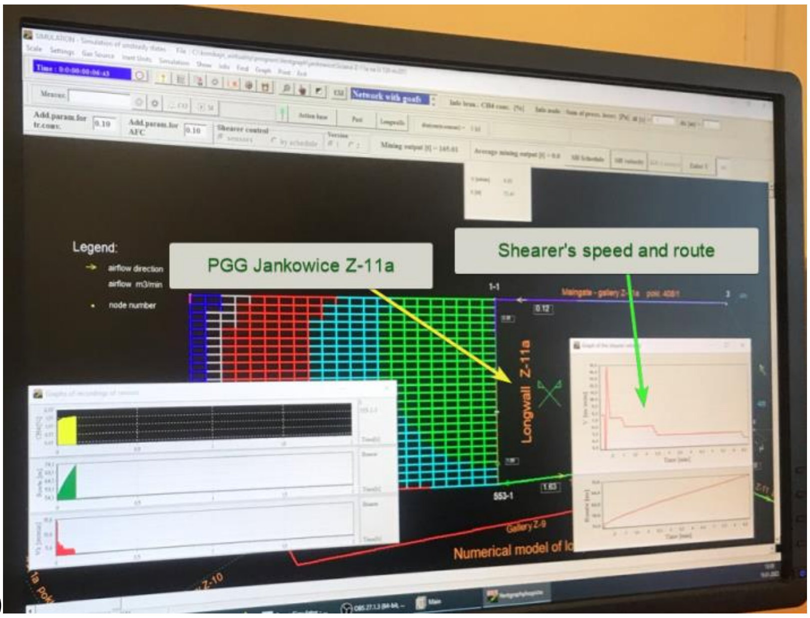
b) 

Figure 43. a) PMV Velenje Bk-95 longwall simulation with Eickhoff shearer; b) PGG Jankowice Z-11a longwall simulation with Eickhoff shearer

During the software tests, we checked what happed when to shearer operator wants to change speed manually during automation work. In some cases caused by safety reasons, the operator should change the shearer's speed or stop the shearer. Such actions have been performed successfully.

The test bench was used for the simulation of two cases, two longwalls: Jankowice Z-11a and PMV Velenje mine Bk-95. Figure 43 shows VentGraph-Plus 's screen during the simulation of PMV Velenje Bk-95 longwall with Eickhoff shearer and the simulation of PGG Jankowice Z-11a longwall with Eickhoff shearer. Those demonstrations will be described in following chapters.

11. EXAMPLES OF BENEFITS ASSESSMENT UPON TYPICAL MINING CONDITIONS AT POLISH SINGLE SLICE LONGWALLS

Prior to the computer simulations potential benefits of controlled shearer operation may be asseesed upon relatively simple analyses. Current chapter presents an example of estimations made for typical Polish longwalls subjected to a methane hazard. For an example representative for the typical single slice longwalls, the same longwall length of 200 m, coal face height 2.5 m, cut width 0.8 m, air volume 1,000 m^3 / min and methane content of the mined coal M_o = 6 m^3CH_4/tonne daf were assumed in the considerations. It was assumed that longwall mining was carried out for three shifts, the fourth for maintenance, and three mining cycles were assumed during the shift. With two one hour travel periods, the actual time of work at longwall is six hours per shift.Three values of a constant cutting speed were analysed, ie 2.5 m/minute, 4 m/minute and 5 m/minute.

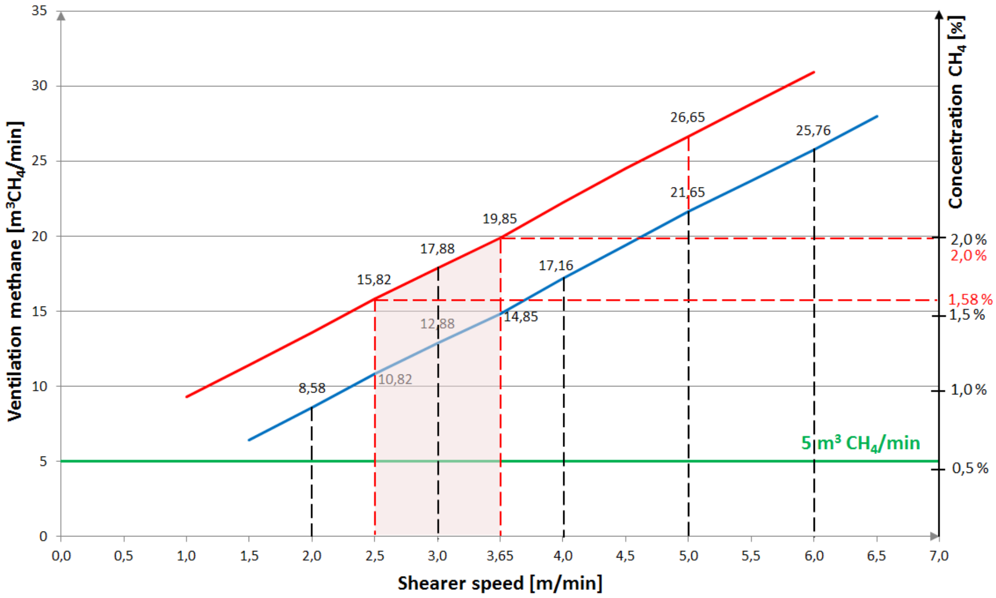


Figure 44. Controlling the speed of the shearer with the "Y" ventilation system The red area provides a limited opportunity to control the shearer speed from 2.5 m/min to 6.65 m/min

Assumptions were made regarding the 15 minute length of breaks necessary for restoring safe methane concentration after the power shutdown triggered by too high methane concentration. Depending on the cutting speed, the value of the methane emission of the longwall increases. It follows from the considerations that during mining on one mining shift there assumed to be, for example, 5 emergency shutdowns, which results in reduced coal production. The conducted analysis of the cases of ventilation of the longwall with the "Y" (Figure 44) and "U" system (**Figure 45**) allowed to determine the cutting speed range between 2.5 m/min and 3.7 m/min, in which there will be no breaks in the cutting, which gives indications for controlled mining cutting speed.

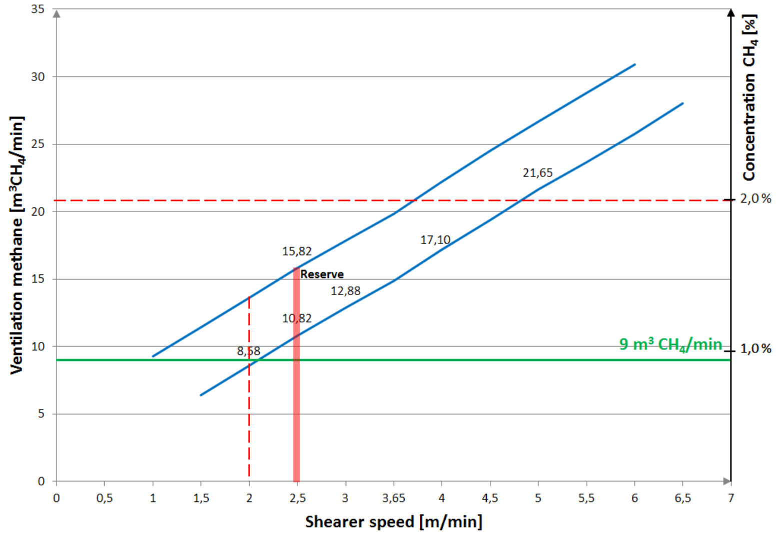


Figure 45. Controlling the speed of the shearer with the "U" ventilation system

Polish mining regulations specify that the permissible ventilation methane level in the longwall district should not exceed 20 m^3CH_4/min in longwalls ventilated in the "U" ventilation system along the coal face. The above-mentioned limitation is related to the existence of a methane hazard in the area of the intersection of the longwall and the tailgate. The volume flux of methane released from the longwall goaf into the tailgate limits the production capacity of the longwall.

In strongly methane-affected longwalls, the stream of methane released from goaf to the tailgate is often in the range of 5-10 m^3CH_4/min. The methane hazard in the area of intersection of a longwall and the tailgate is often eliminated with a specific configuration of auxiliary ventilation equipment and an air-duct supplying fresh air to the longwall exit.

The limiting criterion is the permissible methane flow rate in the longwall district of 20 m^3CH_4/min. The use of classic operational methane drainage in the longwall district captures some of the methane released into the longwall goaf from undermined and overmined seams. Increasing the efficiency of goaf methane drainage increases the potential range of the shearer's control with the "U" ventilation system.

The system for controlling the shearer's speed in a longwall face ventilated with the "Y" system practically eliminates time lost for breakdowns resulting from methane concentrations exceeding 2% at the longwall district exit. Not exceeding the shearer's speed above 3.65 m/min results in the continuity of production in the longwall and in not shortening the time of production cycles.

In summary, longwall faces ventilated with the "Y" system have the benefit of forcing potential methane emissions from the goaf area back towards the goaf and protect the tailgate end of the longwall face from further increased methane concentration. For example, of the extra Q_2 = 600 m^3CH_4/min, which is supplied to the tailgate end of the longwall in the example provided here, counters the amount of methane that can potentially be released from the goaf of the longwall face and provides a saving in the total methane budget, which then can be utilised as production time in the shearer cutting speed control system.

When assessing the benefits of controlling the cutting speed of a longwall shearer, important mining and geological parameters characterising the longwall should be determined. Another factor that was taken into account was the production volume and the amount of methane released. The methodology of the assessment is based on the prediction of typical longwall parameters and the methane inflow data.

12. HOW THE METHANE HAZARD CAN BE REDUCED BY CONTROLLED OPERATION OF THE LONGWALL SHEARER? – THE OPTIMAL CONTROL DEMONSTRATOR APPLICATIONS

The second approach is based on the Virtual Longwall Model of the VentGraph-Plus Mine Ventilation Network environment showing the interaction of the ventilation network, the operation of longwall equipment and adjacent goafs in terms of air flow and gas concentrations. It seems that the second approach allows for a better understanding of the actual ventilation process during the shearer operation.

Important elements for both approaches are to consider:

- ventilation system for the longwall district,
- adjacent goafs,
- operation of the shearer, e.g. in the form of its work schedule,
- operation of the shearer speed regulator system, which transforms the Virtual Longwall Model into the Optimal Control Demonstrator,
- methane balance including the inflow of methane from freshly uncovered coal face and coal transported on conveyors; the inflow of methane from the mined seam, the goafs and from the seams above and below, and taking into account methane drained by the methane drainage system.

12.1. Example 1 – Coal Mine Velenje – Bk-95 longwall

The first example is based on a calibrated model of the longwall Bk-95. The methane concentration records used for the calibration were below the safety treshold, therefore for testing the control system an elevated methane inflow has been assumed. The calculations were performed assuming one mining shift of 6 hours[1]; the operating time of the shearer was assumed as 300 min. during one shift; the stoppage time of the shearer for performing a repeated cutting cycle is 20 minutes (changing the direction of cutting).

[1] Polish work regulations include the time of travel to the workplace. This value has been estimated as one hour. Same value has been assumed for CM Velenje.

The graph in Figure 46 presents changes in cutting speed and the position of the shearer in the longwall as a result of the operation of the regulation system.

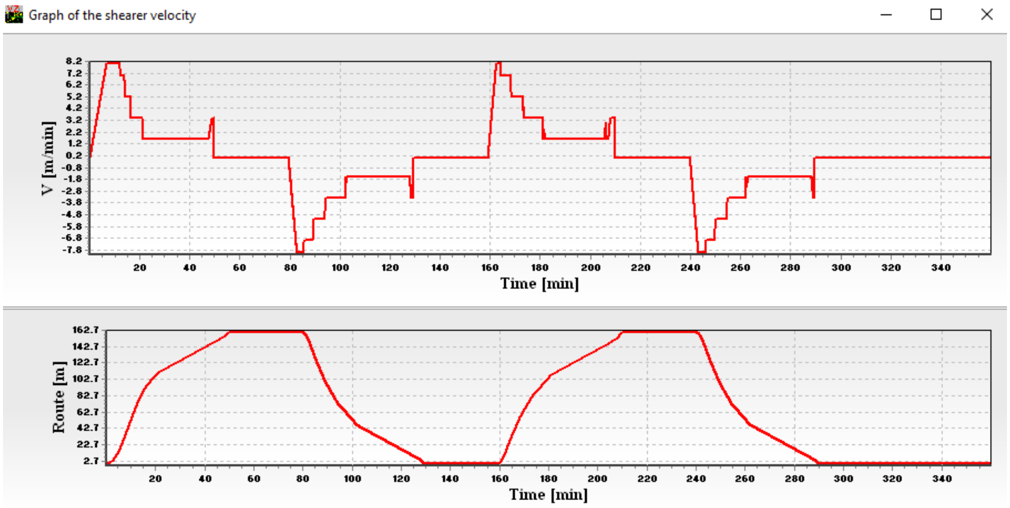


Figure 46. Changes in cutting speed and the position of the shearer in the longwall Bk-95, speed regulation

As a referrence a routine constant cutting speed has been simulated. The graph of Figure 47 presents the progress of cutting and the position of the shearer in the longwall for a constant shearer advancement speed of 4 m/min.

The function of the controller is to minimise the error signal, which is the difference between the input value of methane concentration and the value measured in the air flowing out of the longwall face. The output signal of the controller is a sum of signals of the proportional, differential and integral modules. The amplification factor of the proportional module is responsible for amplifying the error signal; the amplification factor of the differential module is the factor of proportionality between the speed of the error signal change, and the amplification factor of the integral module is the factor of proportionality between the output signal of the module and an integral of the error signal over time.

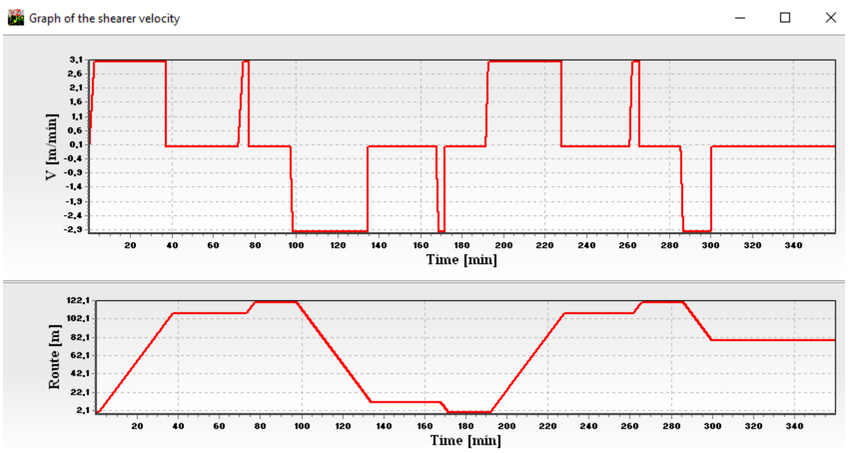


Figure 47. Changes in the cutting speed and the position of the shearer in the longwall,for uncontrolled operation

Depending on the adopted numerical values and conditions of methane emissions from the undisturbed coal mass and the transport of coal on conveyors, the listed parameters of the methane monitoring and the calculation system influence the current advancement speed of the shearer.

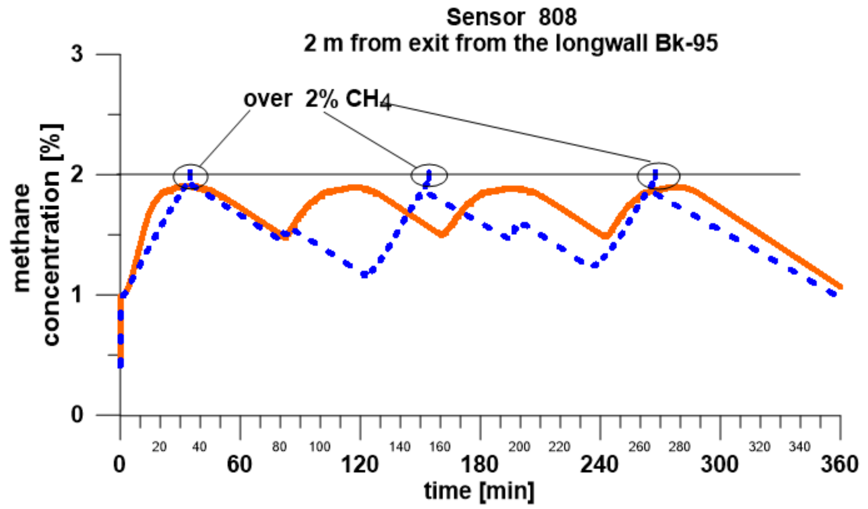


Figure 48. Changes in methane concentration at the the exit of longwall Bk-95, sensor 808, red line – simulation, blue line - monitoring

Figure 48 presents changes in methane concentration for a sensor located at the exit of longwall Bk-95. This sensor controls the cutting speed of the shearer. In the case of the uncontrolled operation (the blue dashed curve), exceeding the 2% level of methane concentration causes the power shutdown and discontinuation of the shearer operation, until methane concentration is reduced below the adopted value of 1.5% CH4.

In the case of a controlled operation (the red curve), which reduces the cutting speed of the shearer in advance, the methane emission is reduced during cutting. Such action does not allow for exceeding the permitted methane concentration. The graph of Figure 49 shows the mining output for the two investigated cases. Higher mining output is visible during the operation of the regulation system. This difference will be discussed in the further chapter.

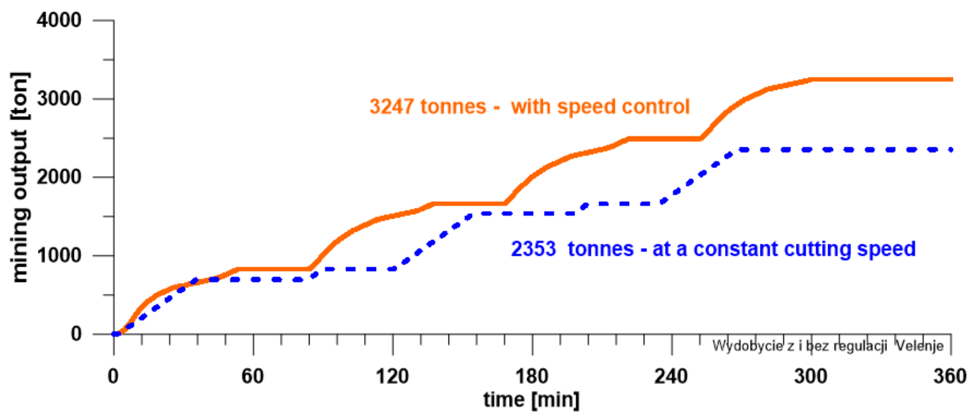


Figure 49. Production volume [tonnes]- red line - with the speed regulation, 3,247 [tonnes] blue line - without the speed regulation, 2,353 [tonnes]

12.2. Example 2 – Jankowice colliery

The second example uses a calibrated model of the Z11a longwall. Also in this case the methane inflow had to be increased. The calculations were performed assuming one mining shift of 6 hours; the operating time of the shearer was assumed as 330 min. during one shift; the stoppage time of the shearer for performing a repeated cutting cycle is 20 minutes (changing the direction of cutting).

The results of the operation of the virtual mining assembly (the shearer and the AFC) in longwall Z-11a are presented in the following figures. The graph of Figure 50 presents changes in cutting speed and the position of the shearer in the longwall as resulting from the operation of the regulation system.

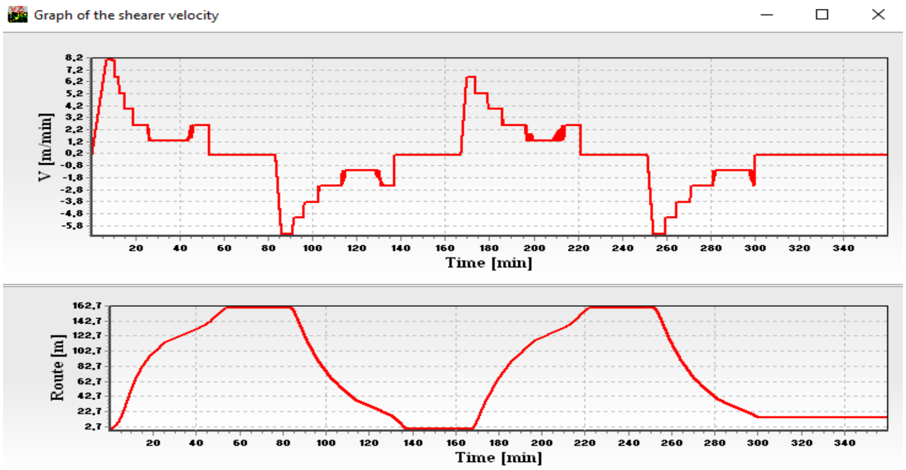


Figure 50. Changes in cutting speed and the position of the shearer in the longwall; speed regulation

In order to check the effects of the calculation system for cutting speed regulation, simulations of shearer cutting were performed for two cases:

- with operation of the control system,
- with a constant cutting speed, meaning with the control system deactivated.

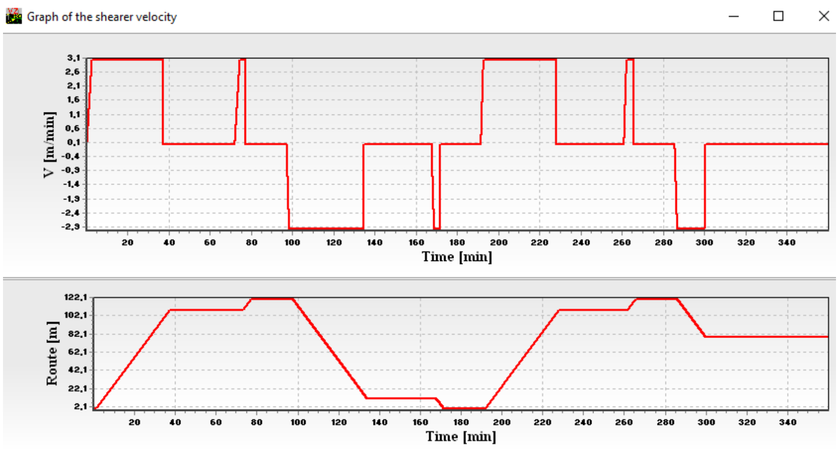


Figure 51. Changes in the cutting speed and the position of the shearer in the longwall, without adjustment

The graph of Figure 51 presents the progress of cutting and the position of the shearer in the longwall for a constant shearer advancement speed of 3 m/min.

Figure 52 presents changes in methane concentration for a sensor located at the beginning of gate road Z-10, carrying the return air from longwall Z-11a. This sensor controls the cutting speed of the shearer. In the case of the regulation system being absent (the blue dashed curve), exceeding the 2% level of methane concentration causes the electric power shutdown and discontinuation of the shearer operation, until the methane concentration is reduced below the value of 1.5% CH_4.

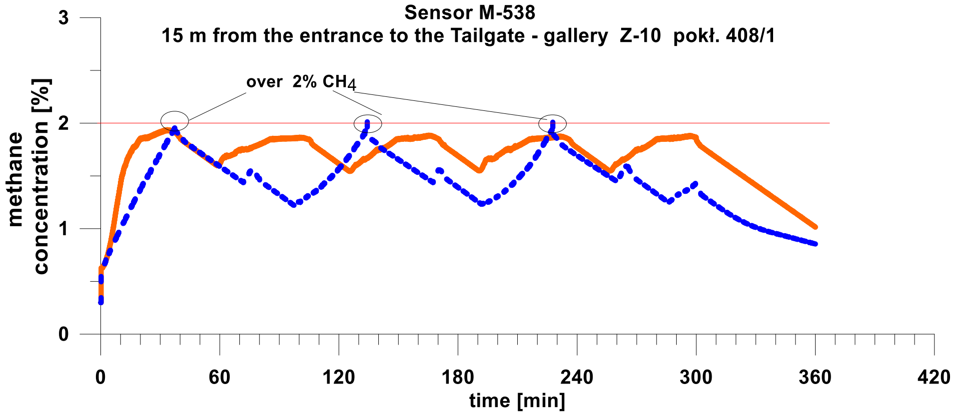


Figure 52. Changes in methane concentration at the inlet of the Z-10 gallery, MM-538 sensor, red line – simulation, blue line - monitoring

In the case of a working regulation system (the red curve), which reduces the cutting speed of the shearer in advance, the methane emission is reduced during cutting. Such action does not allow for exceeding the permitted methane concentration. The graph of Figure 53 shows the mining output for the two investigated cases. Like in the previous example, higher mining output is visible during the operation of the regulation system.

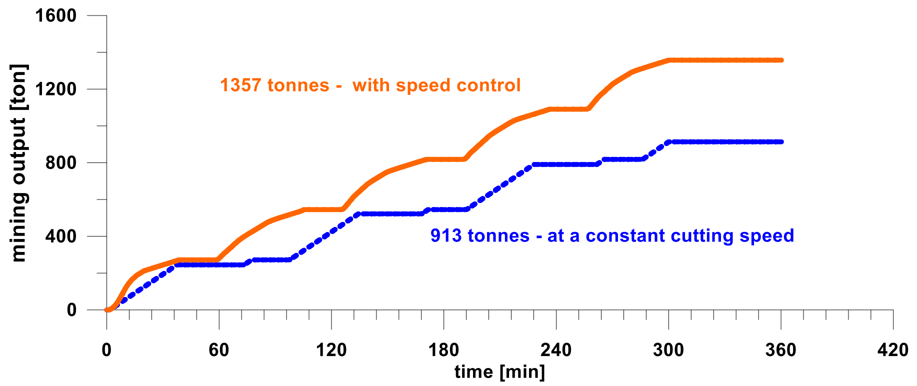


Figure 53. Production volume [tonnes]- red line - with the speed regulation, 1,357 [tonnes] blue line - without the speed regulation, 913 [tonnes]

Reference [Dziurzyński et al. 2020] and video: https://youtu.be/VB_lq1YxiP0 present the example of control for the **longwall 841A of the Bielszowice Coliery**.

So far, the computer simulations have shown that although the control system occasionally slows down the shearer considerably, when the trends in methane concentration are unfavorable, this limitations do pay off, as the flexible cutting velocity settings allow to accelerate when it is possible and protect production from the losses generated by the methane related emergency downtimes.

12.3. Discussion of the results of the control system tests

Analysing the results of a computer simulation of mining with a shearer in the Bk-95 longwall in the Velenje lignite mine, for the conditions of increased methane hazard during mining, we observe the suitability of the control system (Figure 48). Under the conditions of ventilating this longwall, the highest concentration of methane occurs just before its exit from the longwall, in vicinity of the virtual methane sensor providing signal for the cutting speed control system of the shearer. The shearer starts cutting from the inlet side of the Bk-95 longwall and after 7 minutes, when the shearer is located at 28 meters from the beginning of the longwali, it reaches the speed of 8 m/min, . The shearer maintains this speed up to 9.3 minutes of cutting, when the shearer is located at 46m from the beginning of the longwall. Then the control system reduces the cutting speed. Increasing the cutting speed causes increased extraction, we observe greater methane emissions, the concentration of methane increases, the control system gradually reduces the cutting speed to 1.22m/min, then the shearer is at 137m from the beginning of the longwall, time 44 minutes, from the 44-th minute the control system slowly increases the cutting speed of the shearer (Figure 46), in the 53-rd minute the shearer finishes cutting at the end of the longwall.

After the turn around break, the shearer starts cutting upstream of the air , increasing the speed to 6,54 m/min, the shearer is at 151 m, and the cutting time is 86 minutes. Then the control system slowly reduces the cutting speed to 1,24 m/min and in 137 minutes completes the second cutting cycle. The observed work during the 2-nd cycle is repeated for the remaining 3 cutting cycles, with the total production of 3,247 tons (Figure 49).

Analysing the work of the shearer in the BK-95 longwall for the case of switching off the control system, we observe the shearer stops at 122m of the longwall due to exceeding the permissible methane concentration of 2% CH_4 on the sensor located at the outlet of the longwall, (cutting time 35 minutes) the shearer's stoppage lasts up to 76 minutes, then the shearer restarts the excavation, increasing the speed to 4 m/min, the shearer with a speed of 4 m/min is working and completes the 1-st cycle in 92 minutes.

There is a break in the cutting lasting up to 120 minutes, after which the shearer works in the other direction at a speed of 4 m/min. The work of the shearer in successive cycles is similar, and for each cutting cycle a stage when the methane concentration is exceeded is observed (Figure 3 3) and the shearer power supply is turned off. The total production for this case was lower and amounted to 2,353 tons (Figure 49).

For case 2, concerning the mining of the Z-11a longwall in the Jankowice colliery in the initial phase of cutting, for the 1st cycle, there is a noticeable increase in the speed of advancement of the shearer; in the - minute, the speed reaches a value of 8 m/min.; being 26,7 m away from the beginning of the longwall. The shearer maintains this speed until the 10-th minute; when the shearer is located 54m from the beginning of the longwall, after which the regulation system reduces the cutting speed.

An increase in the cutting speed results in increased mining output, with a higher observed methane emission and growing methane concentration; the regulation system gradually decreases the cutting speed to a value of 1.4 m/min., the time is 20 minutes, (Figure 50), and in the 38rd minute, the shearer ends cutting at the 120th metre.

After 20 minutes turn around break, the shearer initiates further cutting, increasing the speed to a value of 5.4 m/min.; subsequently, the regulation system slowly reduces the cutting speed, and in the 105-th minute, it ends the 2nd cutting cycle. The work observed during the 2-nd cycle is repeated for 3 more cutting cycles; resulting in the total mining output of 1,357 tonnes. It is apparent that the regulation system adjusts the cutting speed to the current level of methane emission from the undisturbed coal mass and from the extracted rock being transported.

When analysing the operation of the shearer for the case of the control system deactivated, stoppage of the shearer is observed due to exceeding the permitted methane concentration in the 1-st cycle at the 107,3rd metre of the longwall, upon which the shearer performs cutting for a short time and ends the cutting cycle.

There is a 35-minute break in cutting; until the methane concentration drops below 1.5% CH4, and in the 77-th minute, the shearer ends the 1st cutting cycle. The operation of the shearer in the consecutive cycles proceeds in a similar manner, and in each cutting cycle there are observed cases of exceeded methane concentration (Figure 52) and powering down the shearer. In this case, the total mining output was lower and it amounted to 913 tonnes (Figure 53).

13. EXAMPLES OF BENEFITS ESTIMATION UPON THE USE OF THE OPTIMAL CONTROL DEMONSTRATOR SIMULATIONS

The aim of the research conducted in PICTO was to determine the possibility of controlling the operation of the longwall shearer, in particular its speed, by means of an automatic PID controller (Figure 54). The obtained results show that controlling the cutting speed of the shearer is possible and may result in higher productivity by reducing methane emission reated stoppages (Figure 55, Figure 56, Figure 57).

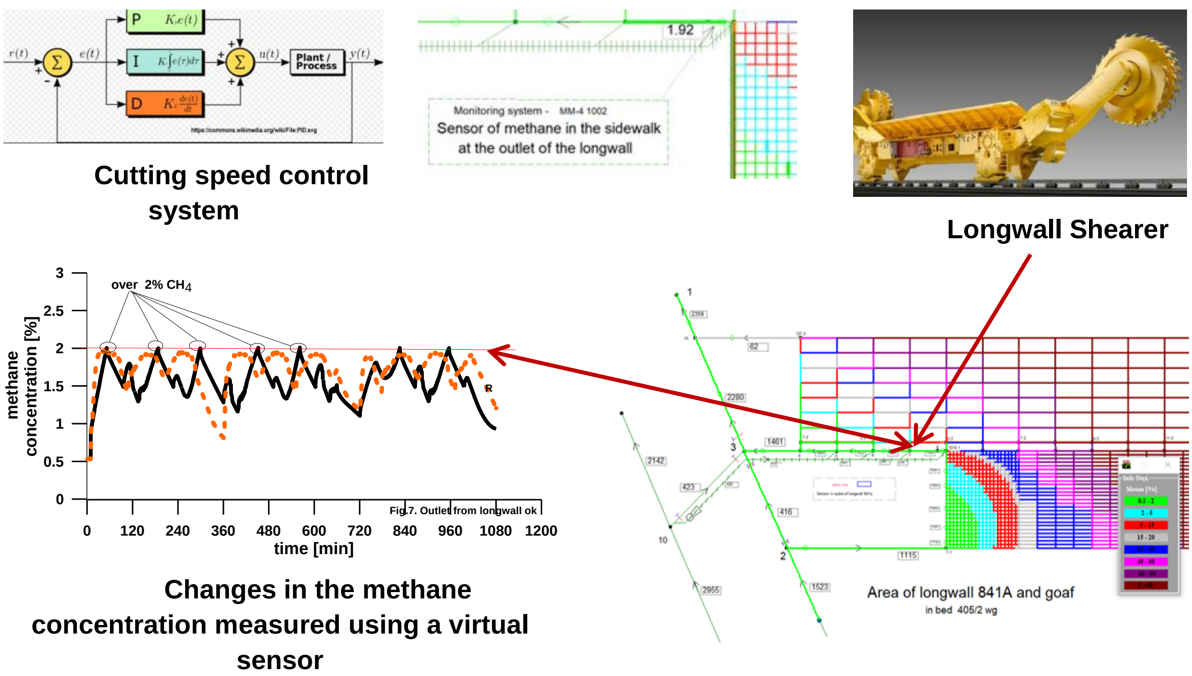


Figure 54. Representation of the longwall mining district with the shearer control system

As part of the project, three examples of simulations of cutting speed control were carried out for the numerical models of three longwall faces calibrated under Task 4.3, where the example of the longwall shearer operation and the transport of the mined coal under conditions of increased methane input was considered:

- Example 1 - longwall 841A in the Bielszowice mine, PGG S.A. Poland.
- Example 2 - BK-95 longwall in Coal Mine Velenje, Slovenia.
- Example 3 - longwall Z-11A, Jankowice colliery, PGG S.A. Poland.

Table 1. Comparison results for the 841 longwall

Bielszowice longwall 841 na "U"				
total methane inflow [m^3] in 300 min		mining [t]	ratio [m^3/t]	difference [%]
7689	with speed control	**1013**	**7,6**	
				5.11
7079	without speed control	**885**	**8,0**	

Table 2 . Comparison results for the LTCC BK-95 longwall

Velenje longwall BK-95				
total methane inflow [m^3] in 300 min		mining [t]	ratio [m^3/t]	difference [%]
9359	with speed control	**3325,6**	**2,8**	
				20,7
8351	without speed control	**2353,2**	**3,5**	

Table 3. Comparison results for the Z11a longwall

Jankowice Z11a longwall				
total methane inflow [m^3] in 300 min		mining [t]	ratio [m^3/t]	difference [%]
6470	with speed control	**1357**	**4,8**	
				22,58
5615	without speed control	**913**	**6,2**	

To calculate the amount of methane released during mining, the time-recorded methane concentration and the flow rate in the return air were used. The calculations were carried out for the case when the cutting speed control system was active, and for reference, the constant cutting speed case was used. Assumed simulation parameters are included in the deliverable reports D4.3 and D5.2, reporting the work carried out in Tasks 4.3 and 5.3.

The obtained results are summarised in Table 1 for longwall 841A of the Bielszowice mine, in Table 2 for longwall Bk-95 of Coal Mine Velenje, and in Table 3 for longwall Z-11A of the Jankowice colliery. The examples presented above concern longwalls ventilated with the "U" system of various lengths and heights as well as the level of methane inflow resulting from the specific mining and geological conditions of a given longwall. For each case, the methane quantity factor [m^3] per production unit [tonnes] (ratio [m^3/t]) was determined.

Figure 55, Figure 56 and Figure 57 show the amount of coal production obtained during the cutting with a shearer with the control system turned on (blue curve), and in the second case with the control system turned off (green curve).

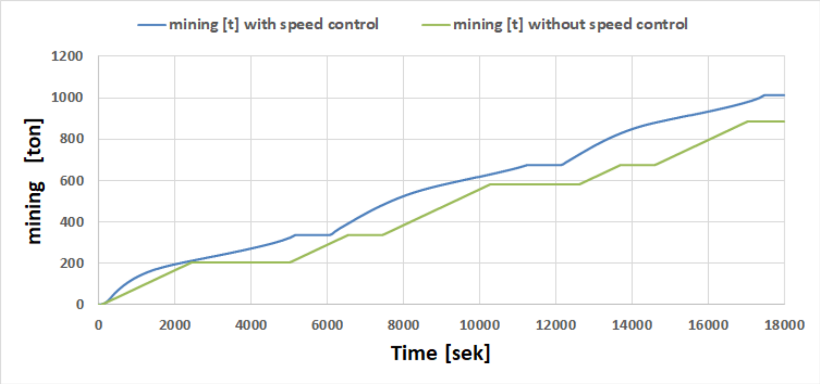


Figure 55. Mining output (tons), Bielszowice longwall 841A

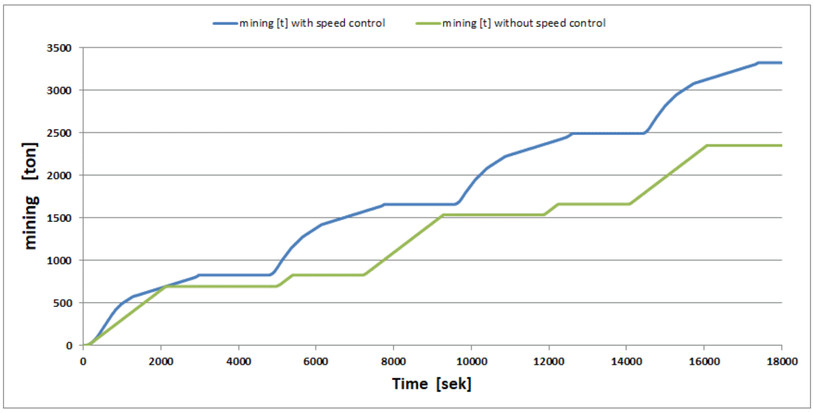


Figure 56. Mining output (tons), Velenje longwall BK-95

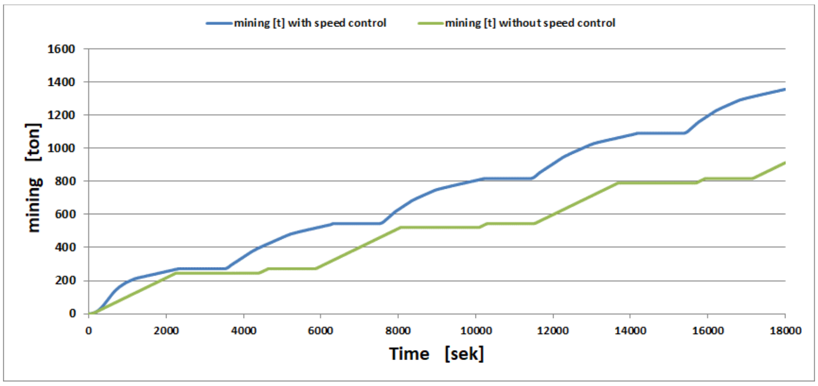


Figure 57. Mining output (tons), Jankowice longwall Z11A

The following Figure 58, Figure 59 and Figure 60 show the amount of methane flow per unit of coal mined during the operation of the shearer with the control system turned on (red curve), and in the second case with the control turned off (purple curve).

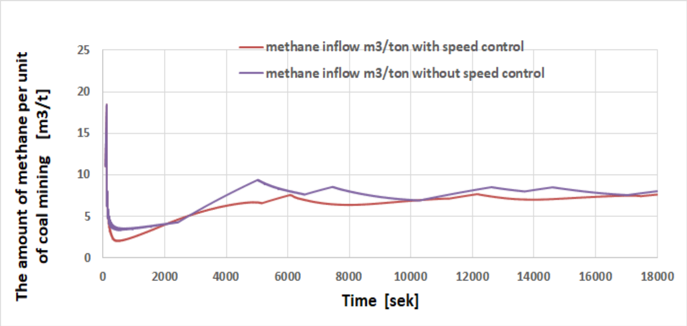


Figure 58. The amount of methane flow per unit of coal mined, Bielszowice longwall 841A

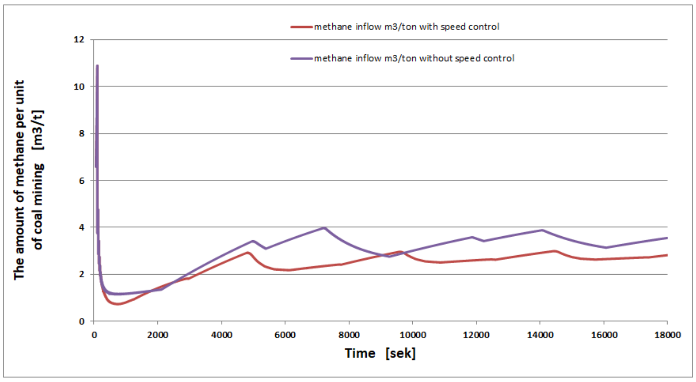


Figure 59. The amount of methane flow per unit of coal mined, Velenje longwall BK-95

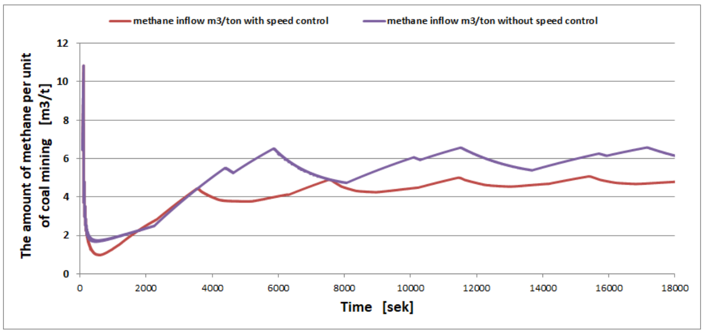


Figure 60. The amount of methane flow per unit of coal mined, Jankowice longwall Z11A

The simulations and calculations carried out show that when the shearer controller is used, the amount of methane released is lower, assuming the same production volume. This conclusion demonstrates the benefits, in terms of mine safety, of the benefits of the use of an automatic system for controlling the cutting speed of the shearer. In column 6 of Table 1, Table 2 and Table 3, the calculated percentage reduction of the methane emission is presented.

Summarising, the use of the controller allowed for higher production while limiting the release of methane into the atmosphere.

14. CONCLUSIONS

In most coal mining regions the mining depth underground has increased, which results in an increase in the methane content of coal seams, which in turn increases the methane hazard. Methane for underground workings is released primarily during the production of mechanically excavated coal, moreover, it migrates from the degassing of the lower and higher seams, as well as from the caved goaf area behind the face. The mines strive to ensure a high economic result, a large amount of coal mined from the available deposits, optimal use of the machinery and the crew. There is a concentration of extraction and an increase in the length and height of the longwalls. It is favored by technological progress, which allows to obtain high speed of progress of both cutting shearers and the efficiency of coal transport equipment. Safety is ensured by methane-monitoring systems with a quick response time. It is becoming problematic to maintain the continuity of the production process and the significant progress of the mining front, especially the longwall front, in the face of mining geological conditions and natural hazards, especially the aforementioned methane hazard. In accordance with the safety requirements, exceeding the indicated threshold concentration of methane in the designated points of the tailgate or the longwall face, causes the electrical power to be turned off, and thus the production process is interrupted. When analysing the reasons for the stoppages of longwall shearers' operation, it should be stated that the methane concentration exceedances are one of the dominant factors in high gas content hard coal mines.

Restart is possible only after the methane concentration has been checked by employees and the safe resumption of the work of the power loader and other transport devices such as the AFC has been confirmed. It should be added that the exclusion also covers stationary lighting devices, as a result the non-productive time is overestimated in relation to the real increase in methane concentration, which is usually of an episodic nature due to a sudden stoppage of cutting.

As already mentioned, the emission of methane depends mainly on the amount of coal mined per unit time. Taking into account the air flow stream through the longwall, the above-threshold methane concentration is local and the concentration takes place directly behind the cutting head in relation to the air flow direction.

The concept of adjusting the cutting speed and the shearer's advance, in response to the current concentration of methane in the stream of air ventilating the front of the excavation and methane emissions during mining is promising. Such action should increase the level of continuity of the production process - mining. Taking into account the complexity of the dynamics of the ventilating air stream and inflowing methane, it is necessary to monitor the aerodynamic parameters, as well as the concentration of methane at the inlet and outlet from the longwall and on the shearer. As a result of the aggregation and analysis of the above data, it is possible to configure a system that would enable effective control of the cutting speed. Such a system should have advantage over the manually set parameters. In addition to the indicated beneficial effects in terms of maintaining the continuity of production, introduction of an additional measurement system at the excavation space is a preventive measure, where actions are aimed at preventing the threshold value from being exceeded. This is a different operation principle than the current shutdown system based on methanometric thresholds - where the shutdown takes place after an exceedance is detected. The speed control concept also increases the safety of the crew.

This view has also been supported by the opinion of Eiskhoff, which as one of the leading shearer manufacturers sees a benefit of the developed system as an additional module of its enhanced automation features which assists the operator underground. As a result the operator will be relieved and be able to focus on keeping the shearer within the geological limits of the cut mineral and also keeping the longwall in a straight position. The higher a longwall operation is automated the higher the production and also safety of it is ensured.

This general knowledge is supported by results of the data analyses namely:

- strong correlation between the increase in methane concentration and the operation of the shearer,
- the impact of mining on changes in methane concentration at the longwall exit was shown
- correlation between the increase in methane concentration and the operation of the shearer during the in situ experiments,
- In the tb103 longwall, seam 414/2, 169 stops of the SL-300 / EP shearer, produced by Eickoff Polonia, were recorded, with a total stoppage time of 13,770 minutes, which amounted to nearly 230 hours, i.e. 9.5 days. It should be emphasised that none of these events, stops, was the result of a shearer failure, and the cause was mining and geological reasons and an increase in methane hazards.

The above-mentioned data indicate the purposefulness of carrying out work in the field of implementation of cutting speed control into practice.

Combined efforts on systematic field monitoring of environmental conditions at longwall districts and numerical modelling of the same using mostly field base data presented in this monograph increased the understanding of the processes behind methane emissions at the face and the flow paths of methane from sources outside the coal seam being mined.

The numerical modelling using CFD and/or coupled geomechanics and flow models produced results which are in agreement with field monitored data, and help understand the processes that lead to the observed emissions and gas concentrations.

In parallel with the analyses of mining environment Virtual Longwall Models providing a realistic representation of real longwalls have been devloped and calibrated.

For those models a prototype of automatic controller has been developed. The controller has been implemented into the Longwall Models to create so called Optimal Control Demonstrator. This software has been used for simulations on calibrated models to test the control system in a safe virtual environment.

In another step towards practical implementation the controller and Virtual Longwall Model have been paired with the hardware and software controlling the real shearer. Simulations comparing effects of controlled and traditional mode of shearer operation carried out for three mines showed the wide possibilities of the obtained benefits. The developed simulation tool provides a lot of cognitive value for the longwall ventilation process in which the cutting is carried out with the control of the shearer cutting speed. The obtained benefits with the use of a Optimal Control Demonstrator depend on a number of adopted parameters, and the selection of parameters of the control regulator itself is of particular importance.

Also the recommended place and number of controll system sensors has been analysed. PICTO has developed and demonstrated that a close loop control system driven by a methane sensor and the prototype controller implemented on the VentGraph-Plus software can control the speed of the shearer. Review of all the PICTO project findings suggests that the next generation of this control system should use more than one methane sensor for this purpose.

The optimum number of methane monitors at the longwall face itself could be 3, placed strategically at the entry to the face, in the centre and at face end. As confirmed by the field measurements and CFD modelling, these should be as close to the roof as possible.

Together with the tailgate methane sensor, either in “U-system”, “short-Y” or “long-Y” ventilation layouts, these 3 longwall sensors can be operated in series, scanned by the shearer control system algorithm with some logic control in such a way that the shearer speed can react to methane peaks developing at the face, or those at the tailgate, depending on the conditions. This would help mitigate against increased methane concentration conditions often experienced towards the end of the production week, such as Fridays.

Summarising, the use of the controller allowed for higher production while limiting the release of methane into the atmosphere. After ATEX certification and underground trials, implementation of this system in the production machinery will be a fully innovative approach to the automation of longwall operations in methane hazard conditions, aimed at:

- increasing productivity and safety by reducing the number of emergency downtimes,
- limiting the presence of the crew in the longwall district,
- limiting the negative environmental impact of the uncontrolled release of methane from coal mines, and
- reducing the strain the operating components of both the longwall shearer and the Armoured Face Conveyor experiences due to regular stop-start processes at the face.

Apart of attaining the general Project objectives its activities provided several additional benefits, namely:

- development of the in-situ expeiments and mine monitoring records database, which has a potential for reuse in further research and analyses
- design and construction of measuring systems like the mobile and flexible mulipoint simaultaneous velocity and methane concentration measuring system based on the extensible scaffold, a probe for visual inspection of boreholes and methodology for an automatic analyses of acquired borehole surface images,
- CFD techniques for modeling airflow, emission and propagation of gases in vicinity of mobile mining devices

15. REFERENCES

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16. GLOSSARY

Calculation system - a system that calculates the feed speed of the shearer based on the measured methane concentration and its rate of change.

Data aggregation - Data aggregation is any process in which information is gathered and expressed in a summary form, for purposes such as statistical analysis. A common aggregation purpose is to get more information about particular groups based on specific variables.

Data cleaning - Data cleansing or data cleaning is the process of detecting and correcting (or removing) corrupt or inaccurate records from a record set, table, or database and refers to identifying incomplete, incorrect, inaccurate or irrelevant parts of the data and then replacing, modifying, or deleting the dirty or coarse data.

Data Exploration -. Data Exploration is about describing the data by means of statistical and visualization techniques. We explore data in order to bring important aspects of that data into focus for further analysis.

Data filtering - Data filtering is the task of reducing the content of noise or errors from measured process data. It is an important task because measurement noise masks the important features in the data and limits their usefulness in practice

Data mining - Data mining is the process of discovering patterns in large data sets involving methods at the intersection of machine learning, statistics, and database systems

Data smoothing - Data smoothing is a statistical technique that involves removing outliers from a data set in order to make a pattern more visible.

Digital twin - a digital twin is a virtual representation of a physical object, such as a device, including its attributes and states. When a digital twin is connected live to it's physical counterpart, it enables engineers to improve their decision making when it comes to its operation and maintenance [Elmo et al 2020].

MethanoAnemometer – a measuring device combining a vane anemometer and a gas (methane) sensor

Mine Ventilation Network Simulator – a computer software implementing a one dimensional model of flow in mine ventilation networks

Moving average - The moving average filter is a simple Low Pass FIR (Finite Impulse Response) filter commonly used for regulating an array of sampled data/signal. It takes M samples of input at a time and takes the average of those to produce a single output point.

Optimal Control Demonstrator - Virtual Longwall Model with a Longwall Operation Control System l

PID Controller - proportional-integral-derivative regulator used in automatic control systems, in which the output signal is the sum of the output signals of three components: proportional, integral and differentiator.

Plant - a process or a phenomenon subject to regulation.

Process variable (PV) **–** the quantity associated with the plant subject to regulation as a result of the controller operation

Setpoint (SP) - value of the quantity to be controlled, supplied as an input signal to the regulator, whose task is to keep the process variable as close to the setpoint as possible.

SP-PV error - result of subtracting the process variable from the setpoint

Ventgraph – a brand of a Mine Ventilation Network Simulator developed at the IMG-PAN with extended functionality

Virtual Longwall Model - a derivative of the Mine Ventilation Network Simulator Ventgraph showing the interactions of ventilation network, operation of the longwall equipment and adjacent goaf in terms of airflow and gas concentrations

Virtual Sensor – a method of the simulation data display storage of a point reading of a selected parameter

17. APPENDIX I LIST OF SELECTED POJECT DELIVERABLES

- D2.1 Report on baseline machine performance and face gas and ventilation data
- D2.2 Report on results of systematic face monitoring data collected and analysed at the 2 industrial sites
- D 2.3 Report on CFD analysis and correlation with the systematic monitoring data
- D 3.1 Report on borehole probe development and borehole scanning results
- D3.2 Report on drainage borehole performance monitoring
- D 3.3 Report on drainage borehole numerical modelling
- D 3.4 Report on optimised sensor locations for longwall and LTCC faces and return/tailgates
- D4.1 Database of time-space dependent distribution of methane concentration and velocity profiles in longwall districts and adjacent production zones
- D 4.2 Report on the statistical analysis of data obtained from the longwall production unit and the monitoring systems
- D 4.3 Calibrated virtual model of the "longwall operations and the shearer - goaf - power roof supports" system
- D 5.1 Report on the control algorithms developed for the longwall - sharer control system
- D 5.2 Report on the integration, testing and validation of the production and face environment control system
- D 5.3 Report on the findings of safety and industrial benefits