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## Lessons Learnt document

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# 1. ABSTRACT

The aim of the research project PICTO was to enhance environmental and health risk management at high production longwall districts in coal and lignite mines by the development of an integrated production process and environmental monitoring and control system which would regulate the shearer operation in response to the monitored environmental conditions and eliminate or minimize excessive gas emissions. A video, available at the projects webpage (https://youtu.be/TX61aKmMkNw ) presents a short project overview. Both classical single slice longwalls and Top Coal Caving (aberv. LTCC) systems for thick seams have been considered. Design and testing of the control system was based on the knowledge on the effect of the variable shearer cutting velocity on the methane concentration at longwall. Measurements and modeling provided input for development and calibration of so-called Virtual longwall models which are a kind of “digital twins” of real underground excavation system. Those models are based on customized version of the mine ventilation system simulator Ventgraph. This in house developed software with beyond standard capabilites of considering the effect of shearer on gas emission and the airflow, unsteady gas migration in galleries and adjacent goaf. Such version, termed as the Virtual longwall model has been paired with a PID controller to provide so-called Optimal Control Demonstrator. Prior to the testing of the control system, the Virtual longwall models have been developed and calibrated for longwalls representative for both single slice and LTCC methods. During the calibration, data from the monitoring system and field experiments has been compared with the simulation results. For the calibrated models realistic scenarios have been select to demonstrate possibilities of controlled shearer operation and estimate its advantages (see video https://youtu.be/VB_lq1YxiP0 ). The simulations and calculations performed show that the controlled shearer cutting velocity may result in higher production while limiting the release of methane into the atmosphere. The duration of the Project was too short to enable in-situ underground testing of the control system due to the time required to obtain intrinsically safety certifications compulsory for the explosive gas hazard zones. That is why at the final stage of the control system development performed within the frames of the PICTO project, the Optimal Control Demonstrator has been connected with the real shearer control hardware and software in a workshop conditions on a surface. Due to a special arrangement the original shearer elements could not detect that they operate in a simulation environment. The simulations and workshop tests have confirmed the advantages of controlled shearer operation, opening a way to the underground testing as a follow up of the Project.

## 2. INTRODUCTION

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 in Australia, China, the Czech Republic, Germany, India, Kazakhstan, New Zeland, 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 (Brune et. al. 2017). 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; Cecala et al., 1994). 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 [Fiscor 2017, Peng et al. 2020]. However, so far there is no information on the practical implementation of the shearer automation in controlling hazards associated with the excessive methane emissions.

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. Recently published study [Trenczek et al. 2020], initiated after the start of the PICTO project by a Polish Researach and Development Institute Komag confirms the actuality of the research on the methane hazard reduction by an automated shearer operation.

Difficult and dangerous conditions of underground mine environment, especially when the presence of explosive atmospheres must be considered require an extensive preparatory work in terms of selection and testing of control algorithms in safe conditions. At this stage the concept of automation may be developed with the aid of computer simulations using calibrated models, acting as a kind of the digital twins of the longwall districts. Therefore the main part of assessing the benefits of controlling the cutting speed of a longwall shearer is based on the virtual 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 considering:

- 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 cutting speed regulator system,
- 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.

Subsequent chapters show that the calibration of numerical models and the positive integration and testing of the Eickhoff shearer with the control system confirmed the good consistency of the computational procedures used in the calculation algorithms and the practical application of this model in programs for numerical modeling of mine ventilation networks with goafs. Comparison of simulations with and without the controller showed the true advantages of the controlled operation. Additionally, during the simulations, the current production and amount of methane released (ventilation air methane) were recorded using virtual sensors. The obtained data made it possible to determine the amount of methane per unit of coal mined during the operation of the shearer with the control system turned on, and in the second case with the control turned off.

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

In development and testing of the shearer control system two kinds of models of the longwall districts have been used. The first one is a **Virtual Longwall Model** develped with a customized version of the VentGraph-Plus Mine Ventilation Network simulator. The second one is the **Optimal Control Demonstrator**, which binds the **Virtual Longwall Model** with the actual shearer’s control hardware and software. This bond contains the target PID controller, which is to maintain the operation of shearer within a safety limits regarding the methane hazard. This chapter describes the process of development and calibration of the Virtual Longwall Models for conditions representative for both single slice and thick Top Coal caving longwalls. Both are based on the VentGraph-Plus program, which 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 coal, taking into account the balance of methane emitted during production.

The program evolved from the classical mine ventilation network simulators, using the mesh method for solving the mass flow rates in the network of airwys, where the system of nonlinear mesh equations is solved with the Hardy Cross method [Barczyk 1935, Cross 1936, Hinsley and Scott 1951]. Initial objective was to perform simulations of unsteady propagation of gases in a ventilation network released during the gas and rock outburst [Dziurzyński et al 1987]. Introduction of a fire source model was a next step of development.

Knowing the air density, the mass flow rates may be transformed into the volume flow rates. For a given cross sectional area the air velocities are calculated, which in turn allow for modelling of the propagation of fire gases or methane in the mine's ventilation system and evaluation of their effect on the buoyancy.

The solver of the Ventgraph uses so-called quasi-static approach. Its properties are:

- ventilation system of the mine is represented as a network, closed through the atmosphere,
- for each node of the network mass balances for the mixture of air and contaminating gases (methane, products of fire) are formulated,
- the network is treated as a set of meshes. For each independent mesh another balances are formulated.

They constitute a set of flow equations. Prior to the simulation, this set is solved, giving initial values of flow quantities in branches. During the unsteady flow simulation, for each time step:

- the propagation of contaminant gases and heat exchange is evaluated,
- then new temperatures of air are known, thus
- new densities are calculated.

Change in density in branches results in:

- new resistances of branches,
- altered natural ventilation pressure.

Therefore new flow quantities are calculated for the next time step.

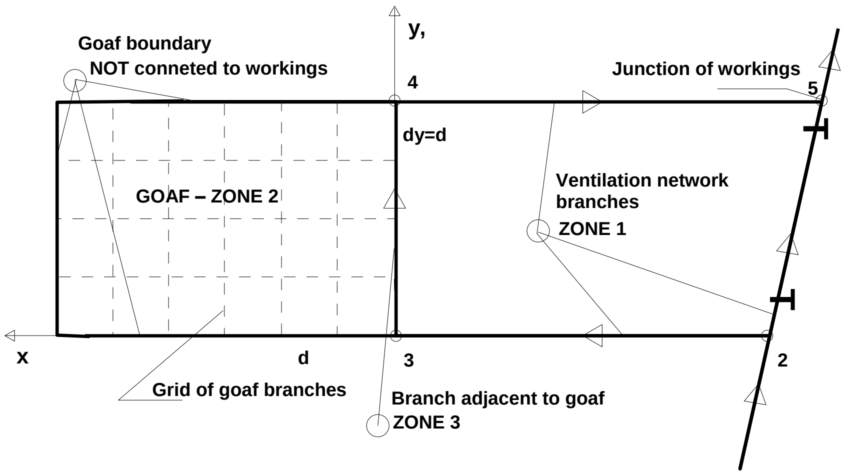


**Figure 1. VentGraph-Plus - the idea of connecting mine ventilation networks with the grid of goaf branches**

In subsequent development step the network model has been be extended with rectangular goaf areas [Figure 1]. The goaf region is replaced by the network of perpendicular branches, representing linear filtration in the plane determined by the given coalbed. Thus, the same numerical model of branches can be both used to handle turbulent flows in mine headings as well as linear filtration processes in the goaf. The model has been described in [Nawrat 1999, Dziurzyński 2002], and [Dziurzyński et al. 2007, 2010, 2010a] present the results of the comparison of the methane concentration curves recorded by the methane meters of the geometry system in Bielszowice and Budryk mines to those obtained from computer simulation using the VentGraph software.

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 [Dziurzyński et al. 2019].

The new and innovative software has been developed by a team from IMG PAN, with intention to be used for the purposes of the Project by industrial partners. The VentGraph-Plus software enables numerical simulation of the shearer operation and of controlling its speed depending on the inflow of methane to the longwall area.

Transients generated by variable inflow of gases, fires or outbursts of gas and rocks lead to a complex distribution of parameters in a ventilation network, which vary both in time and space. Simulation of such phenomena is beyond the scope of application of most Mine Ventilation Network Simulators [Krawczyk et al. 2019]. A few developers worldwide have extended the functionality of their products to the unsteady phenomena. For VentGraph this feature has been developed since the beginning, using results of some in-home research and benefiting from a sequence of research and validation projects.

The presentation of unsteady phenomena requires additional resources. As regards spatial distribution, branches of the network are divided into segments. Values of i.e. methane concentration or temperature of air in a section are displayed as a particular color. Thus the network scheme is transformed into a map of i.e. methane distribution. During the simulation these distributions may vary with time, transforming a scheme into an animated colored map. This solution allows the observation of fluctuations during simulation. In contrast to steady states computations, information about individual colors for presentation is displayed (e.g. distribution of oxygen concentration levels in fire gases). Another advantage is the possibility of obtaining time diagrams of observed parameters in selected network points (by placing virtual sensors). The application of a solution with a legible color screen makes the interpretation of phenomena occurring in the network much easier.

Due to the properties of the Virtual Longwall models listed above they may be considered as a kind of Digital Twins of the longwall systems operating in the methane hazard conditions, which makes them suitable for development and testing of the target closed loop shearer control system. In order to conduct further research to determine how methane concentration changes during production methods 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.

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 paired with the records of a normal shearer operation provided an uniqued dataset.

After calibration, the ***VentGraph-Plus*** model was sufficiently accurate for both the event and normal operation, which justifies application of such models for the forecasting of the effects of the shearer control. After such confirmation of the model validity, models of the Z11a and B k. -95 longwalls investigated within the project work packages have been calibrated.

## 3.1 NUMERICAL MODEL OF THE BK-95 LONGWALL DISTRICT

Data on the estimation of methane inflow to the B k. -95 longwall district during mining, the average amount of air 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 additional fresh air to the longwall face outbye end. A ventilation diagram of the longwall district is shown in **Figure 2**.

The target model contained a set of elements, namely:

- ventilation system of the longwall district,
- the adjacent goafs,
- operation of the shearer,
- 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
- operation of the shearer speed controller, activated during the controlled operation testing.

To determine the parameters of the numerical model of the goafs of the Bk-95 longwall, the 3D modelling of gas migration in the adjacent strata affected by the longwall performed by Imperial College have been used to develop a numerical model, the ventilation scheme of which is shown in Figure 2. After analysing the available data, the geometry of the goaf and its properties like distributions of porosity and permeability have been determined.

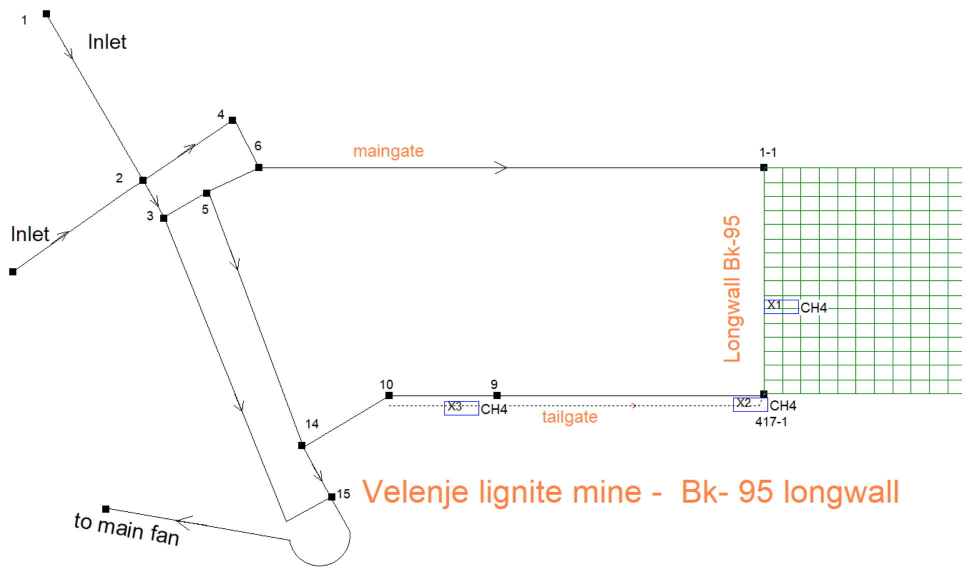


**Figure 2. Numerical model, ventilation scheme of the B k. -95 longwall district with grids of goaf branches; dashed line - separate ventilation, X1 $CH_4$ - methane sensors of the monitoring system**

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.

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 longwall 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.

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 $m^3$/ min, according to measurements the average flow rate the wall was 1,728 $m^3$/ min,
- the volumetric air flow rate in the tailgate was 2,105 $m^3$/min, including additional 234 $m^3$/min supplied by an auxiliary ventilation system.
- the methane concentration at the location of No. 51 sensor (CH4_51) was 0.48 %.

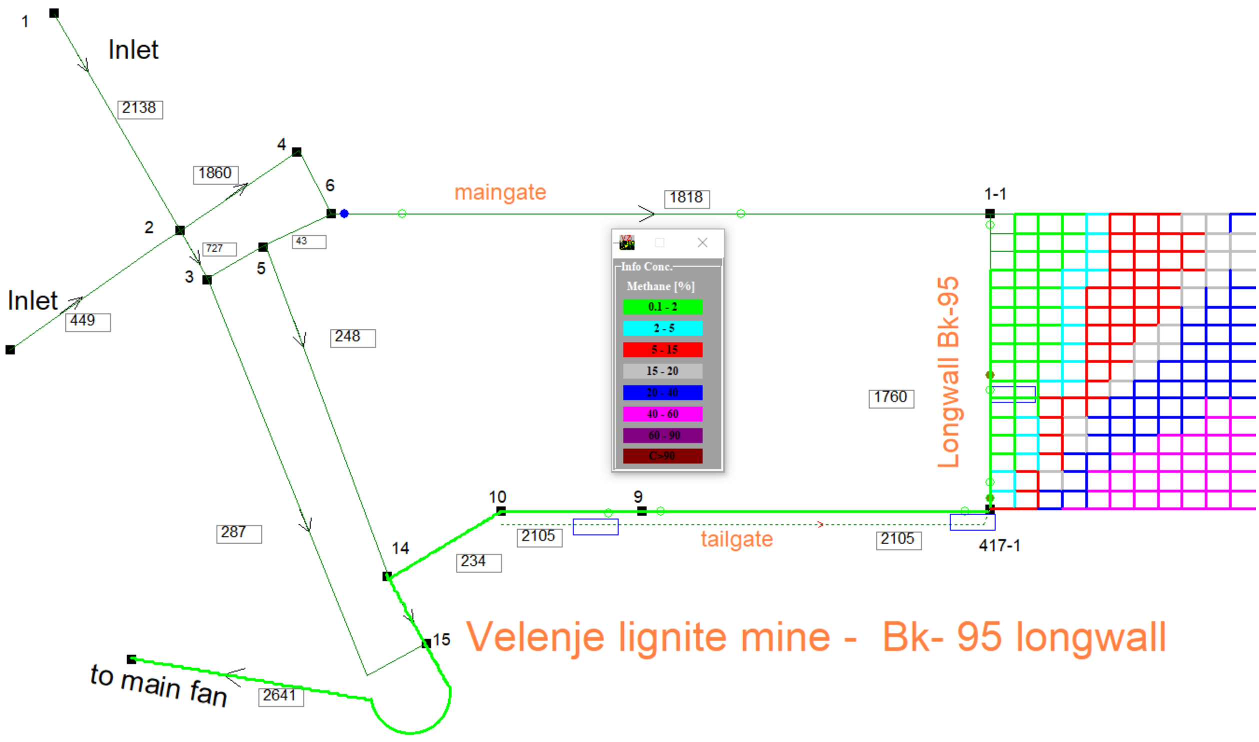


**Figure 3. A ventilation scheme of the B k. -95 longwall district with grids of goaf branches, coloured bold lines – distribution of methane concentration in longwall goafs, - rectangles show the air flow volume stream ($m^3$/min); arrows show the direction of flow; numbers at junctions highlight their identification**

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 3 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.

### 3.1.1 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.

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.

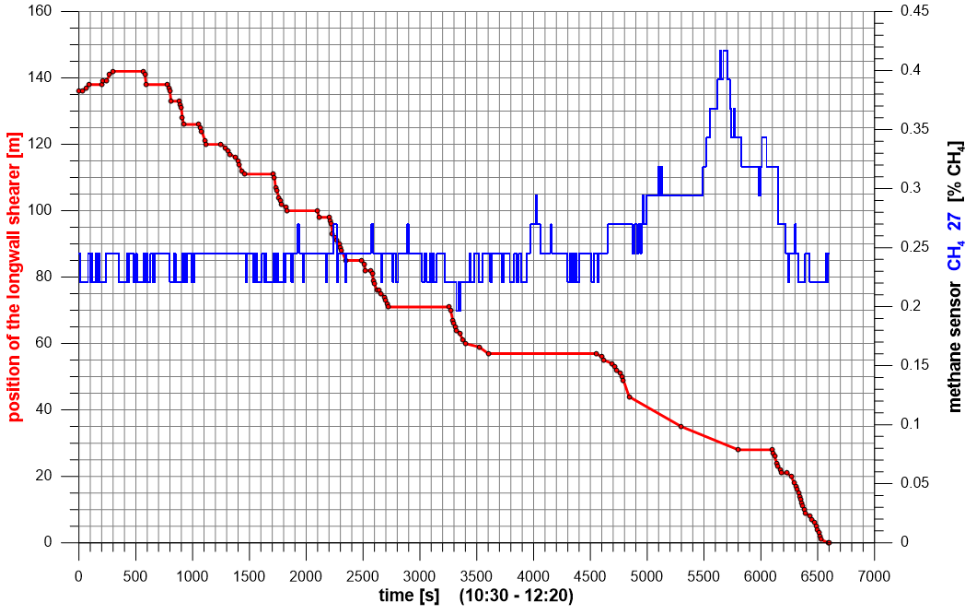


**Figure 4. Longwall shearer operation as a function of time - red line, methane concentration changes for sensor CH4_27 - blue line.**

Based on the graph (**Figure 4**), 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 4, 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 5 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.

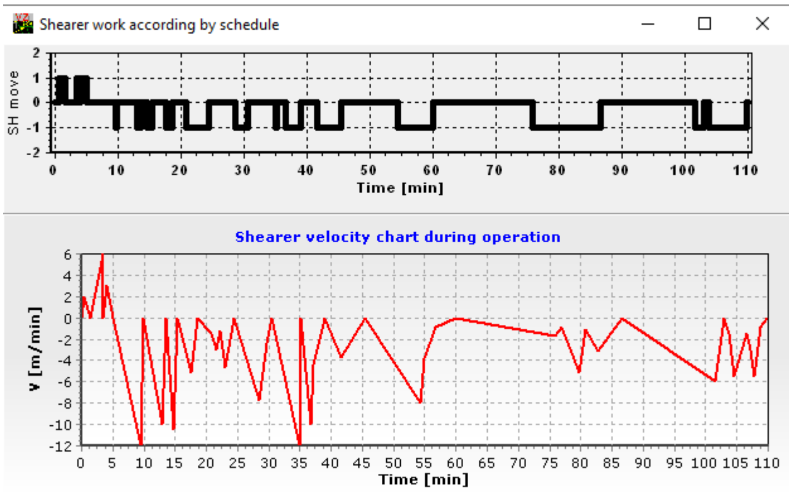


**Figure 5. Changes in the shearer's cutting speed as a function of time - red line, shearer operation in the longwall: 1- cutting towards the longwall outlet, 0-standstill, -1 cutting towards the inlet against the air flow - black line.**

The main features of the schedule (Figure 4, Figure 5) 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 4); 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 order to properly assess the effect of the shearer on the environmental conditions at longwall several parAmeters 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 web depth, initial cutting speed of the shearer, speed of excavated material (output) transport on the armoured face conveyor at longwall and conveyers system 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 $CH_4$-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 6 shows the predicted (dashed orange line) and recorded (using the sensors of the monitoring system) (solid black line) methane concentrations.

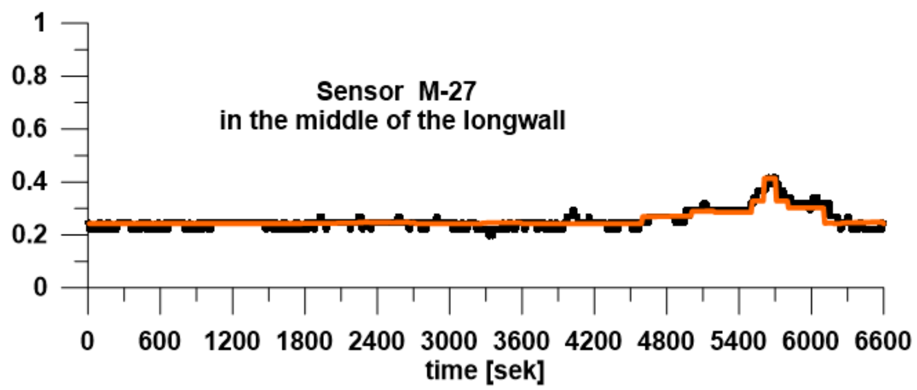


**Figure 6. Changes in methane concentration in the middle of the longwall, sensor $CH_4$-27, orange line – simulation, black line - monitoring**

The time series of changes in methane concentration recorded by the sensors of the monitoring system, 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.

## 3.2 NUMERICAL MODEL OF THE Z11A JANKOWICE COLIERY LONGWALL DISTRICT

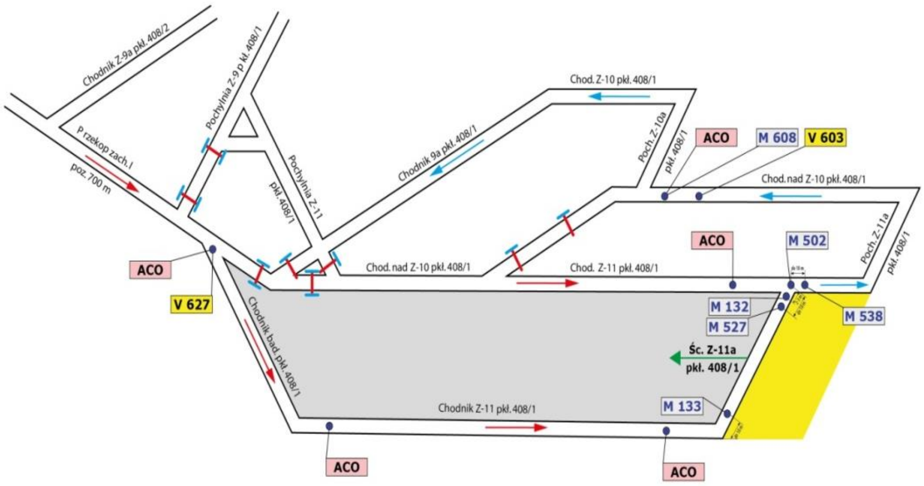


**Figure 7.** Scheme of the Z-11A longwall in seam 408/1 with the monitoring system sensors.

Using the same  mode a model of the Z11a Jankowice colliery longwall for the Y ventilation system has been developed. The longwall scheme is shown in **Figure 7**.

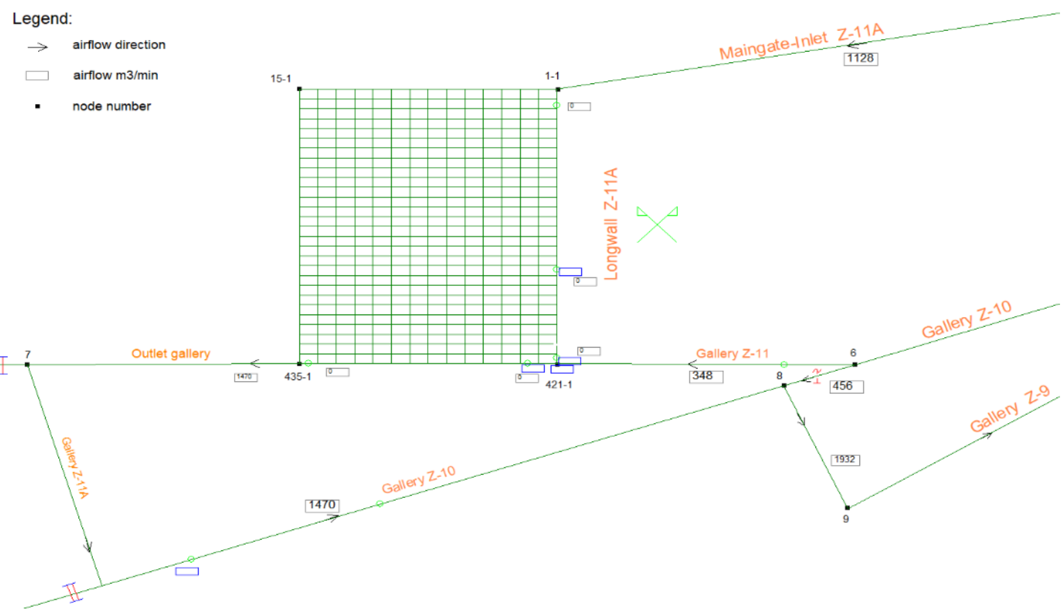


**Figure 8. Numerical model of the Z-11a longwall district with grids of goaf branches in rectangles showing the air flow volume stream ($m^3$/ min), with arrows showing the direction of flow and numbers at junctions highlighting their identification.**

### 3.2.1 CALIBRATION OF THE Z11A LONGWALL NUMERICAL MODEL

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. 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.

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 8**). The developed schedule is shown with the red line in Figure 9, the blue line shows the course of changes in methane concentration measured by the MM-608 methane sensor located in the Z-10 longwall.

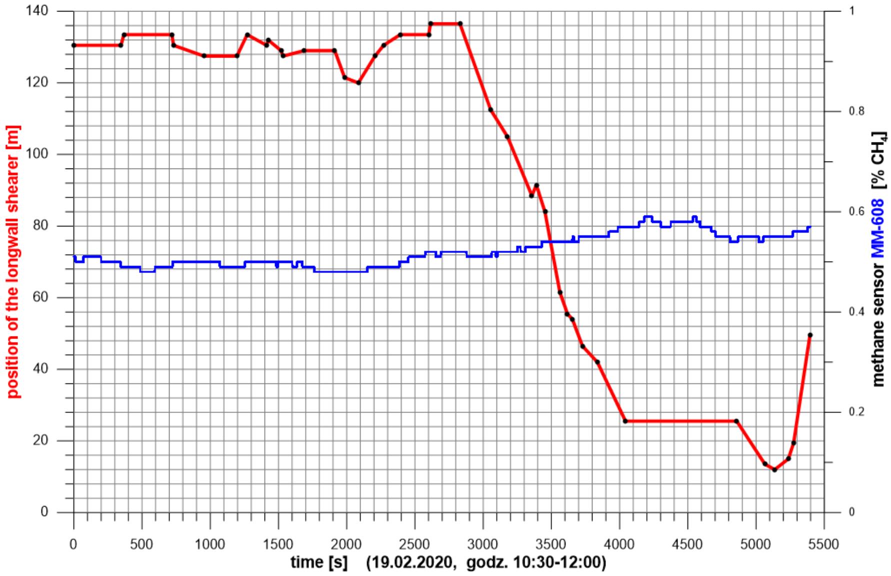


**Figure 9. Longwall shearer operation as a function of time - red line, methane concentration changes for the MM-608n sensor - blue line.**

Figure 10 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.

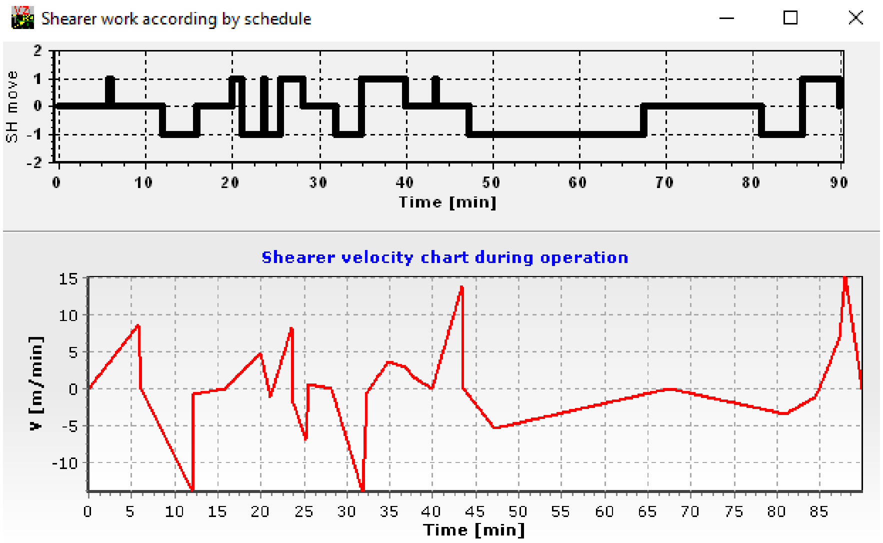


**Figure 10. Changes in the shearer's cutting speed as a function of time - red line, shearer operation in the longwall: 1- cutting towards the longwall outlet, 0-standstill, -1 cutting towards the inlet against the air flow - black line.**

The shearer moves in the Z-11A longwall according to the presented schedule (**Figure 10**)

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 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 11** to **Figure 12** show the predicted (dashed orange line) and recorded (using the sensors of the monitoring system) (solid black line) methane concentrations.

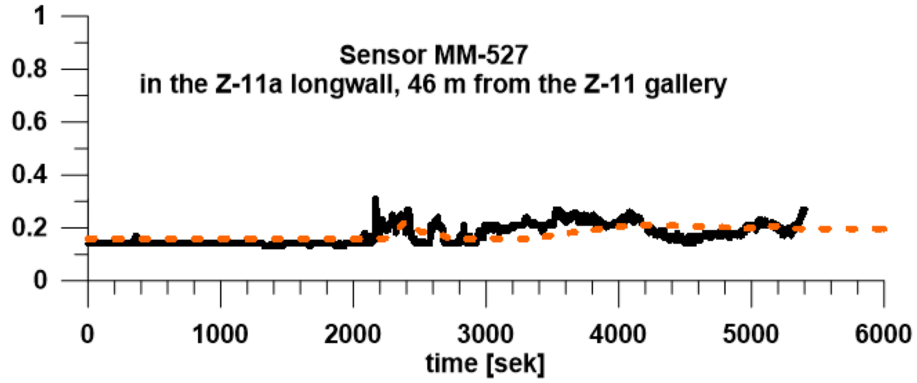


**Figure 11. Changes in methane concentration 46 m from the longwall outlet, MM-527 sensor orange line – simulation black line - longwall monitoring**

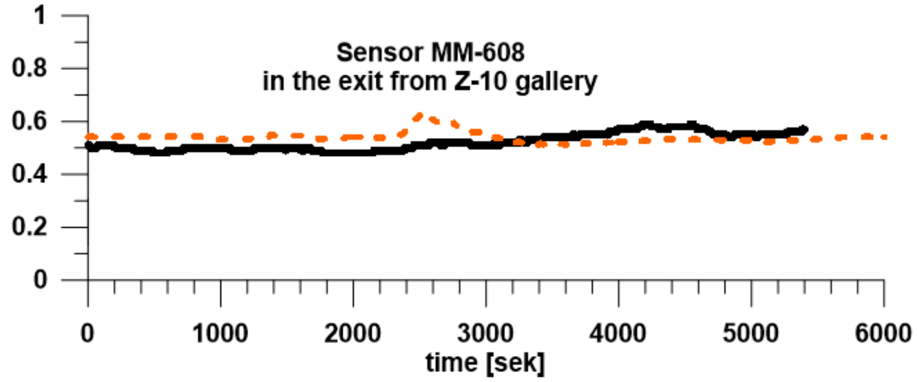


**Figure 12. Changes in methane concentration at the inlet of the Z-10 gallery, MM-608 sensor, orange line – simulation, black line - longwall monitoring**

Validation of the mathematical model used in the software and calibration of the numerical models of the longwalls analysed in the PICTO project 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.

# 4. DEVELOPMENT, TESTING AND VALIDATION OF THE PROTOTYPE REAL-TIME ENVIRONMENTAL MONITORING AND CONTROL SYSTEM

## 4.1 IDENTIFICATION OF CONTROL OBJECTS BY DEFINITION OF INPUT, OUTPUT AND INTERFERENCE VARIABLES

Development of the closed loop control system required establishing the objective of control as maintaining methane concentration in the longwall district below the value permitted by the regulations. Next, using the known dependence of methane concentration in the air current flowing out of the longwall on the intensity of winning, i.e. the increase in methane concentration along with an increasing flow of the extracted mass, it was necessary to define the object of control. This task, leaded by IMG PAN required a close co-operation and information exchange with Eickhoff, Imperial and GIG

The object of control is the longwall district production with adjustable shearer cutting speed, a longwall AFC conveyor, a haulage gate conveyor and with methanometers of the gas monitoring system. The object of control is characterised by parameters describing the environmental conditions and safety conditions in the longwall being extracted by the shearer. In the object of control, one can distinguish input and output signals, as well as interference.

Input signals include the advancement speed and cutting range of the shearer, the speed of the longwall conveyor and the conveyor in the haulage gate road. Among the input signals, the control signal of the object has been identified, which is the advancement speed of the shearer. The output signals are: the flow of extracted mass and methane concentration along the longwall and the haulage gate road. The output control signal is the signal from the methanometer at the outlet of the longwall. Additional output control signals are signals from methanometers distributed along the longwall. Interfering signals are categorised as measurable and immeasurable. Measurable interfering signals here are the volumetric flow rate of air flowing to the longwall and methane concentration in this flow, while immeasurable interference includes: the distribution of density of the volumetric flow rate (speed) of methane flowing out of the undisturbed coal mass of the longwall without winning, the distribution of methane flow rates out of the undisturbed coal mass in front of the shearer as well as that in a zone of fractures caused by winning, and the distribution of methane flow rates out of the exposed undisturbed coal mass behind the winning shearer [see Dziurzyński et al. 2019].

The identification of signals, as well as the data from the literature and from underground measurements in mines, have allowed for the development of a mathematical model of a longwall area being excavated by a shearer. 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.

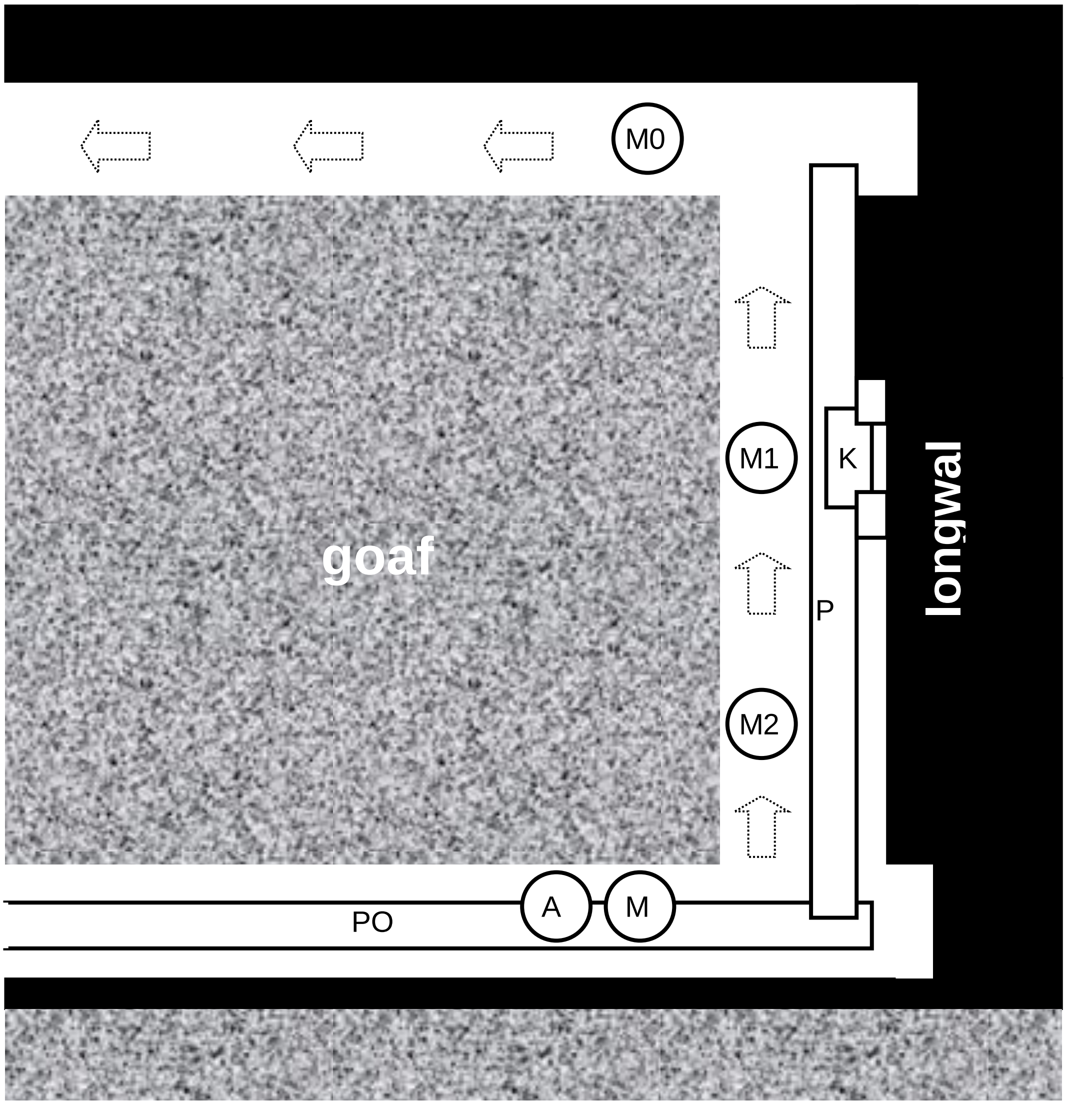


**Figure 13. Controlled object: The area of longwall with a cutting shearer.**

Symbols: 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

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. 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..

## 4.2 DEVELOPMENT OF PROTOTYPE OF PRODUCTION UNIT CONTROL ALGORITHMS AND PROCEDURES

Identification of the object of control and the generation of a numerical model of the object allow for developing prototypes of control algorithms. This task was done by IMG PAN with co-operation with Eickhoff combining the expertise in modeling with a campetence in development and practical implementation of the control systems. The objective of control, which is maintaining methane concentration in the longwall below the permitted value, is intended to be achieved by an automatic regulation system with a closed feedback loop. 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 allowable 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 the treshold value. 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 14** presents the diagram of the control system.

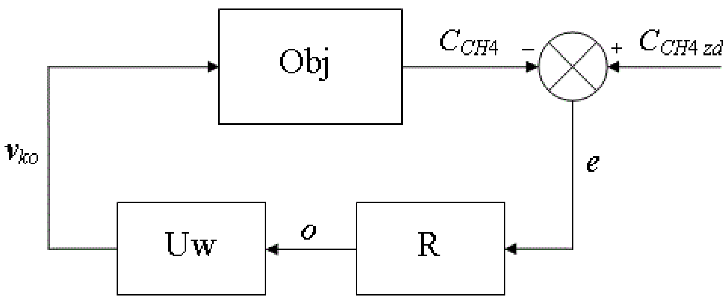


**Figure 14. The control system of methane concentration at the outlet of longwall mined by a shearer.**

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 % for Poland).

The output (PV) from the controlled object consists of methane concentration, $C_{CH4}$, measured by a methanometer in the top road at the longwall outlet. The methanometer should be placed at a point in the road where the highest methane concentration is expected.

In the numerical simulation of controlling the shearer, this is a virtual methanometer placed in the longwall at the outlet, or in the gate road near the outlet.

The process variable (PV) from the controlled object is deducted, at a summing node, from the setpoint (SP) which is the present value of methane concentration, $C_{CH4\ zd}$, resulting in the error signal, $e$ = SP - PV.

The error signal, **e**, is fed to the input of the proportional-integrating-derivative (PID) controller. The coefficient for the proportional term, **P**, is equal to the ratio of the element output signal to the input signal. The coefficient for the integral term, **I**, is equal to the ratio of the output signal increase rate of the element, in response to a stepwise signal, to this signal value. The coefficient for the derivative term, **D**, is equal to the ratio of the element output signal to the rate of the linear input signal increase.

The rate of the measured methane concentration change is provided by the following relationship:

$$v_{CH4} = \frac{C_{CH4}(t_k) - C_{CH4}(t_k - \Delta t_0)}{\Delta t_0} \qquad (1)$$

where $C_{CH4}(t_k)$ is the measured methane concentration,

$t_k$ is the time, where $t_k = k \cdot \Delta t$, and $k$ is the time step.

The output signal of the controller is fed to the input of the **Uw** system, which at a zero-output signal of the controller gives the calculated shearer speed, $v_{ko}$, which is equal to the initial shearer speed, $v_{kp}$, and – at a decreasing output signal of the controller, which is a response to the growing measured methane concentration – reduces the calculated shearer speed.

$$v_{ko} = v_{kp}\left(\frac{o}{C_{CH4\,zd}} + 1\right) \qquad (2)$$

The generation of numerical algorithms for the operation of the methanometer and the PID controller with a summing node and an output system allows for testing the work of the automatic regulation system for methane concentration in the longwall by way of numerical simulation, using the VentGraph-Plus software, by adjusting the advancing speed of the winning shearer. The VentGraph-Plus software allows for performing the simulation with numerical models of longwalls of actual underground coal mines.

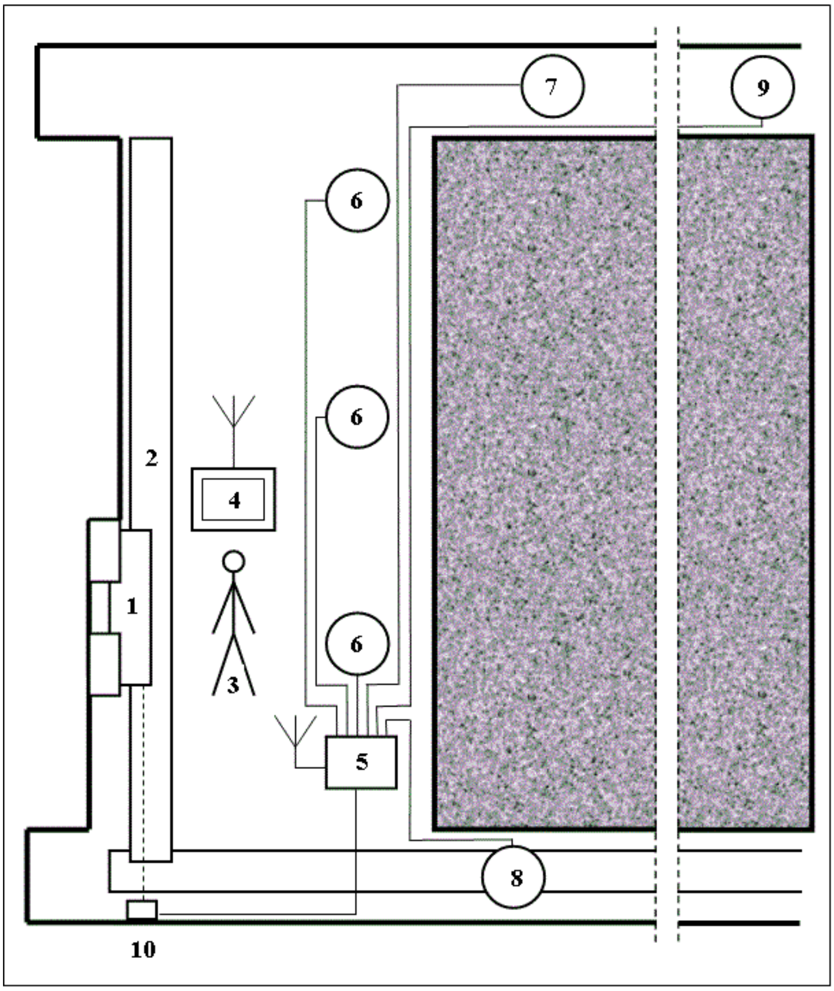


**Figure 15. System for automatic adjustment of shearer advancement speed with multi-point methane concentration measurements and with the shearer operator in a feedback loop.**

Symbols: 1 – shearer, 2 – longwall conveyor, 3 – shearer operator, 4 – readout panel, 5 – calculation system, 6 – longwall methanometers, 7 – methanometer in the top gate road, near the longwall outlet, 8 – methanometer in the haulage gate road, near the longwall inlet, 9 – methanometer in the top gate road, distant from the longwall, 10 – system for measuring the position of the shearer in the longwall.

As it has been stared in the Task 3.4 conclusion, the variable gas dynamic conditions of the extracted seam suggest the introduction of the elements of adaptive control by distributing additional methanometers throughout the longwall, taking over control at a proper time and position of the winning shearer in the longwall (**Figure 15**). The development of proper algorithms for control with multi-point measurement of methane concentration in the longwall allows for testing such solution by way of a computer simulation. Parameters of the longwall area model are to be calculated from the results of the records of methane concentration and the path of the shearer, taking into account the periods of winning and travelling without winning, performed in the modelled coal mine longwall. Settings of the PID controller can be calculated from the trend of methane concentration at the start of winning with a constant shearer advancement speed, after a longer longwall stoppage, as recorded by the control methanometer. Properly selected parameters of the longwall and controller model ensure a credible result of numerical simulation of the process of automatic regulation of methane concentration in the longwall.

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

Potential effects of may be assessed by application of the Optimal Control Demonstrator of the VentGraph-Plus Mine Ventilation Network environment considering:

- 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.

## 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).

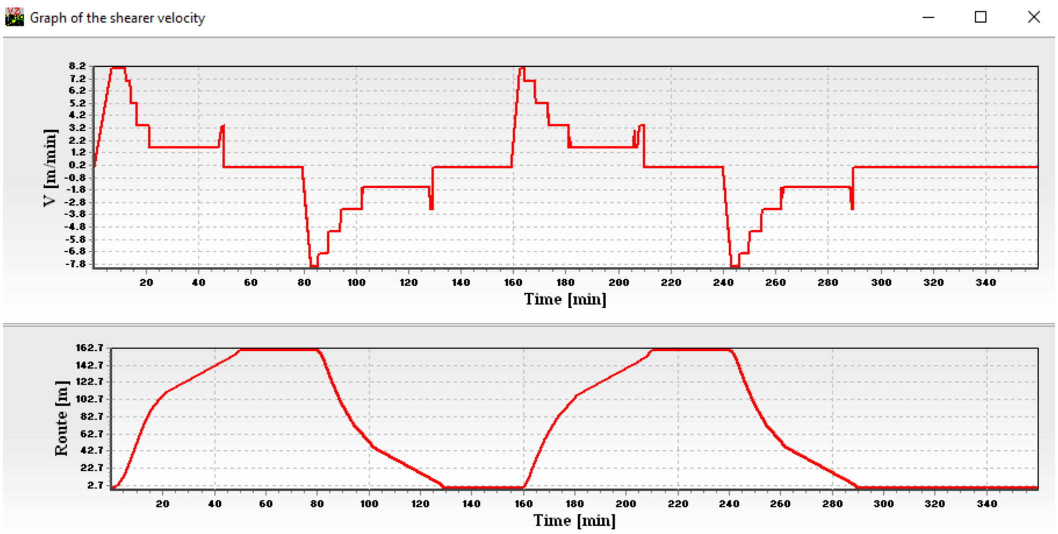


**Figure 16. Changes in cutting speed and the position of the shearer in the longwall Bk-95, speed regulation**

[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 16 presents changes in cutting speed and the position of the shearer in the longwall as a result of the operation of the regulation system.

As a referrence a routine constant cutting speed has been simulated. The graph of **Błąd! Nie można odnaleźć źródła odwołania.** Figure 17 presents the progress of cutting and the position of the shearer in the longwall for a constant shearer advancement speed of 4 m/min.

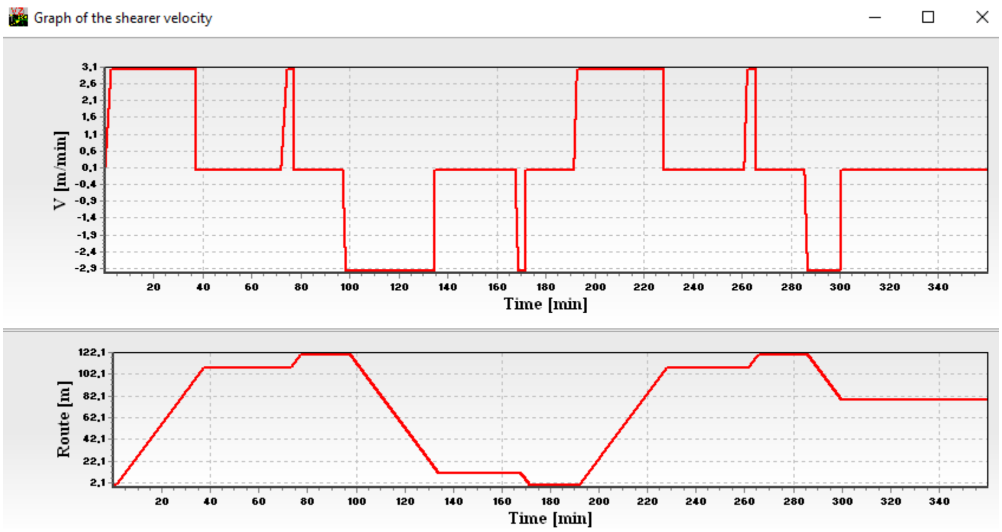


**Figure 17. Changes in the cutting speed and the position of the shearer in the longwall,for uncontrolled operation**

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.

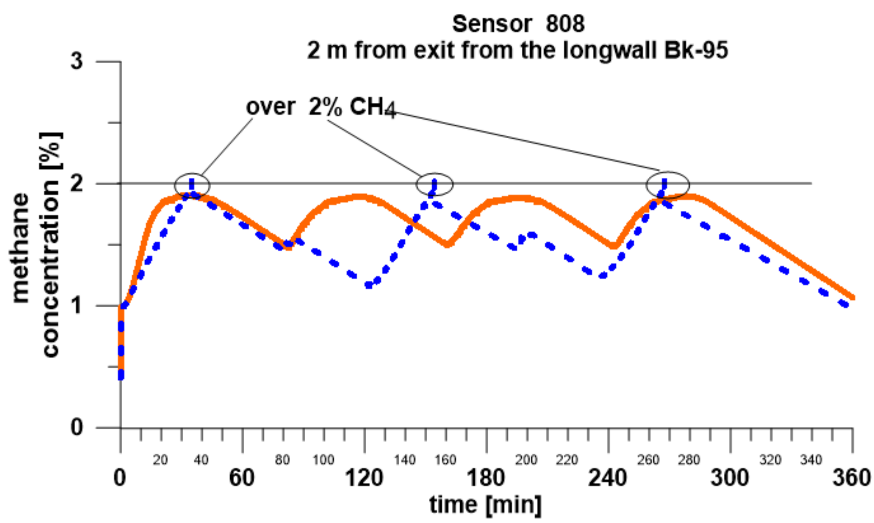

**Figure 18. Changes in methane concentration at the the exit of longwall Bk-95, sensor 808, red line – simulation, blue line - monitoring**

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 18 Figure 18** 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% $CH_4$.

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.

## 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 19**Błąd! Nie można odnaleźć źródła odwołania.** presents changes in cutting speed and the position of the shearer in the longwall as resulting from the operation of the regulation system.

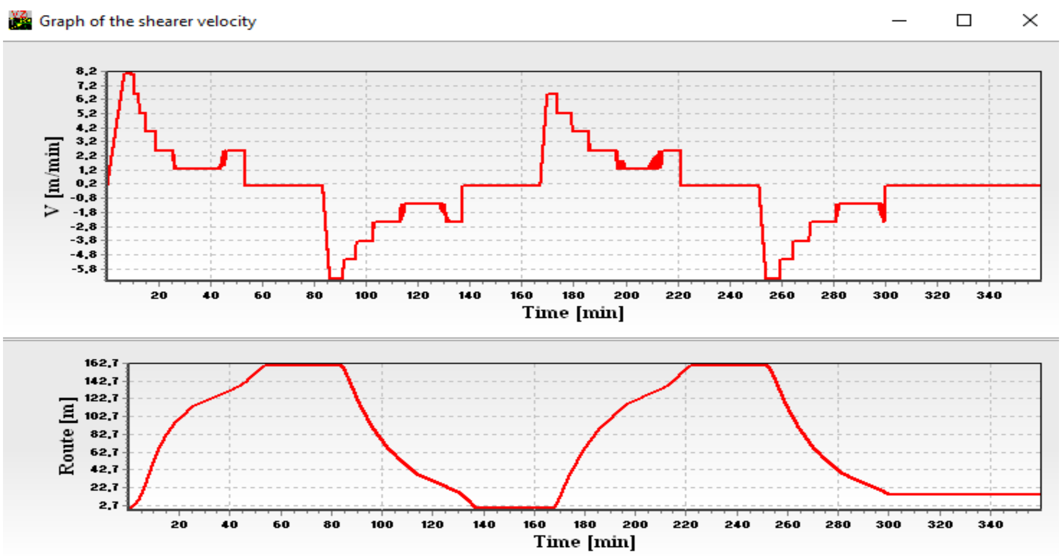


**Figure 19. Changes in cutting speed and the position of the shearer in the longwall; speed regulation**

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.

The graph of **Błąd! Nie można odnaleźć źródła odwołania.** Figure 20 presents the progress of cutting and the position of the shearer in the longwall for a constant shearer advancement speed of 3 m/min.

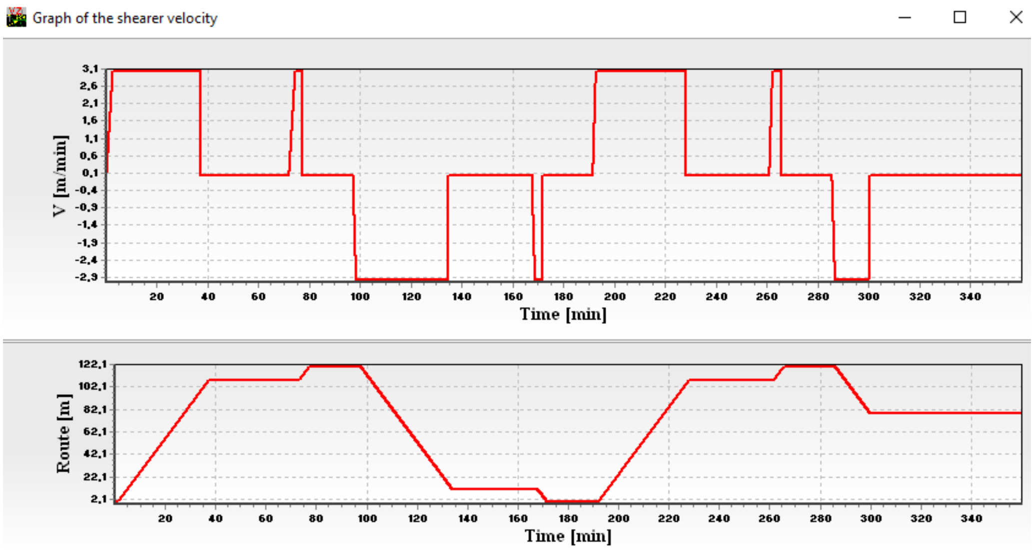


**Figure 20.** Changes in the cutting speed and the position of the shearer in the longwall, without adjustment

**Błąd! Nie można odnaleźć źródła odwołania.** Figure 21 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% $CH_4$.

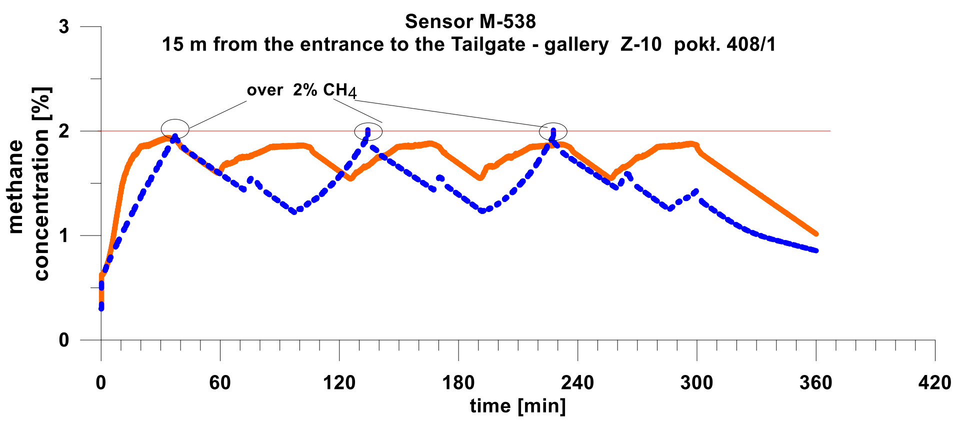


**Figure 21**. Changes in methane concentration at the inlet of the Z-10 gallery, MM-538 sensor, red line – simulation, blue line - monitoring

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.

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.

# 6. A STEP TOWARDS PRACTICALIMPLEMENTATION – TESTING THE CONTROL SYSTEM CONNECTED WITH THE SHEARER CONTROL HARDWARE AND SOFTWARE

Testing of the controlled operation of longwall subjected to a methane hazard has been done both in a pure computer simulations and after the integration of the shearer's hardware and software with the target control system. The second task has been guided by Eickhoff, who apart of its expertise provided an IPC industrial computer and know-how necessary for transfroming it into a standalone laboratry test system connected with the Ventgraph's Optimal Control Demonstrator. Deliverable D5.2 of PICTO contains a more detailed desription of this task illustrated with two video recordings of a live control system operations

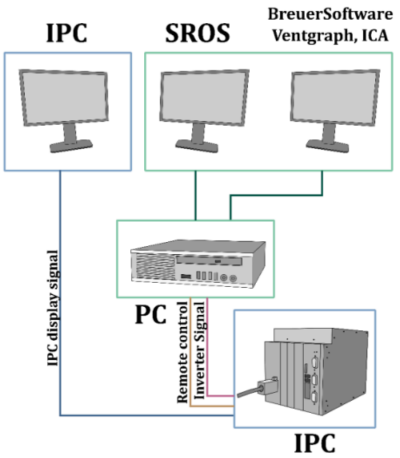



**Figure 22. Shearer control system – Production Unit Control. IPC (Industrial Power Computer), SROS – enables remote control by the operator, PC allows to computer virtual longwall's model.**

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As it has been stated in the introduction, 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 [**Figure 22**]. 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 function as if it they have been placed in a shearer.

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 hve been implemented in the shearer software by Eickhoff. 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. 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.

a b

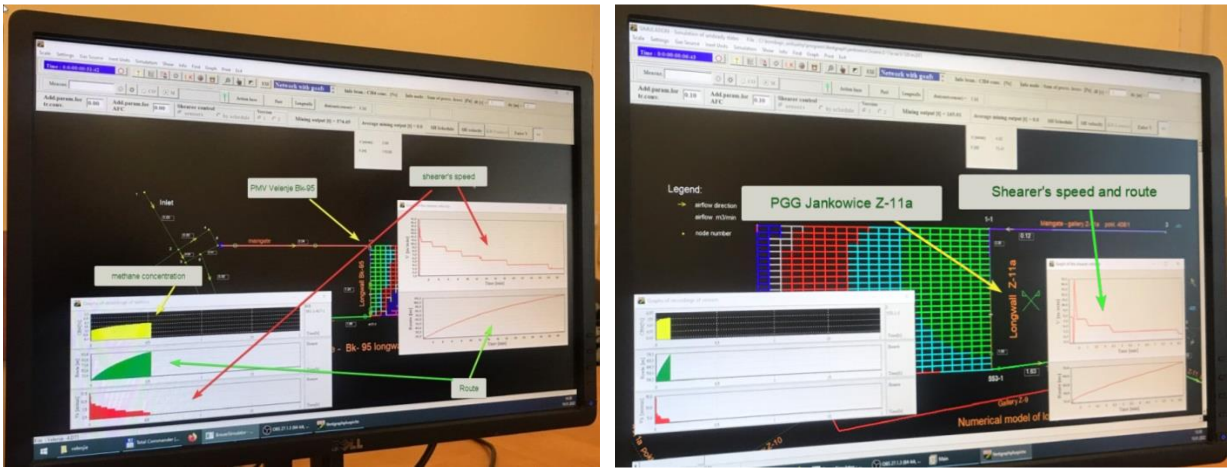


**Figure 23** . a) PMV Velenje Bk-95 longwall simulation with Eickhoff shearer; b) PGG Jankowice Z-11a longwall simulation with Eickhoff shearer.

The test bench was used for the simulation of two cases, two longwalls: Jankowice Z-11a and PMV Velenje mine Bk-95. **Błąd! Nie można odnaleźć źródła odwołania.** Figure 23 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 the Eickhoff shearer. During these tests a functionality of the shearer operator manual intervention also has been tested.

During this tasks several simulations for both single slice and LTCC longwall shave been performed. Their aim was to test and tune the control system and then to assess the potential of the new solution by comparison of controlled and not controlled operation of longwall. The outcome from those comparisons may be presented on two selected examples.

In the tests carried out within the scope of the project's Work Package 5 the so-called Optimal Control Demonstrator, using the Eickhoff's "virtual shearer" has successfully implemented the shearer's cutting speed settings adjusted by the control system in response to the methane concentration level measured by a virtual methane sensor. Such control has prevented exceeding the preset (2% CH4) permissible level of methane concentration during the operation of both longwalls.

In the examples, this sensor was located at the longwall outlet, this is the place where the highest concentration of methane is expected, it should be noted that both the conducted experiments and the analyzed results of the monitoring system records and the CFD simulation studies confirm such a location of the control sensor. In order to learn more about the control object, it is recommended to conduct research with the use of, for example, two or three sensors controlling the control system.

The obtained simulation results using previously calibrated numerical models of longwalls provided new knowledge in the selection of parameters of the control system, and in particular the amplification of individual elements of the PID controller. In summary, the successful implementation of the Eickhoff virtual shearer control tests using calibrated versions of the Virtual Longwall Models implemented in the VentGraph-Plus program allows for further development of methods for the safe and economic exploitation of single-layer coal (PGG) and thick (LTCC) coal seams. The integration, testing, validation and demonstration of the operation of the longwall shearer's operation control algorithms and procedures as part of the bench tests provided a lot of experience for technological development and constitutes a preparatory study for the formulation of a demonstration project. Further work, going beyond the scope of the PICTO project must include underground testing of the control system which requires the ATEX certification.

# 7. EXAMPLES OF BENEFITS OF CONTROLLED OPERATION ASSESSED WITH THE VIRTUAL LONGWALL MODEL AND OPTIMAL CONTROL DEMONSTRATOR SIMULATIONS

The airflow and methane analysis processes are too complex to easily predict the effectiveness of individual solutions. Empirical search for a solution in a place operating in a potentially explosive atmosphere is too risky. The proposed simulation tests make it possible to investigate the problem.

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 24Figure 24).

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.

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.

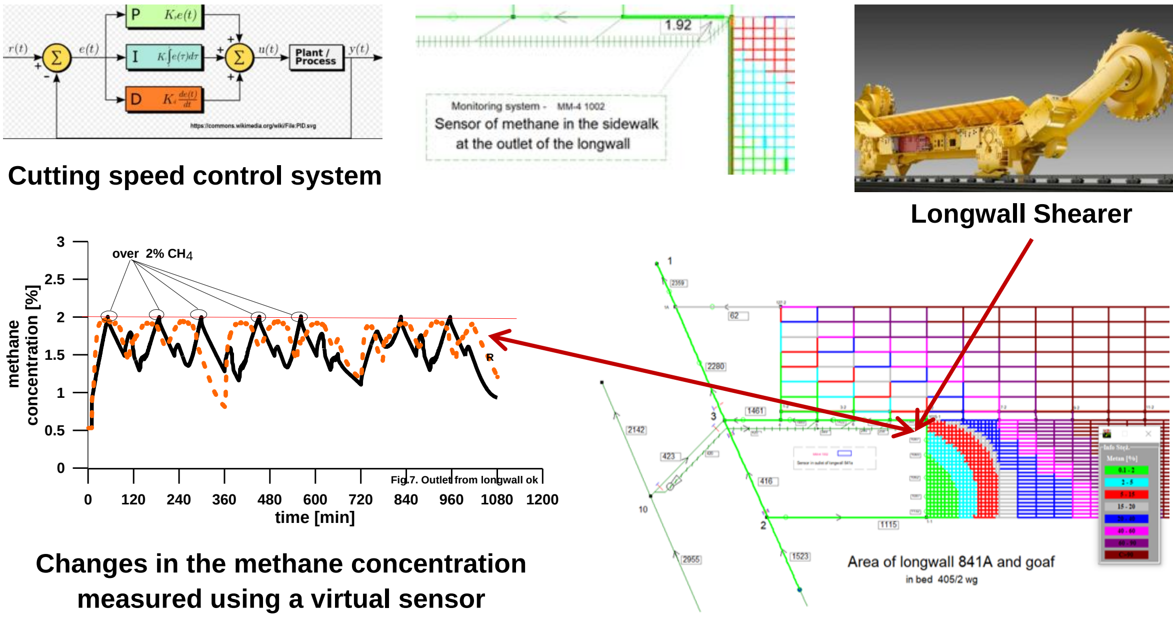


**Figure 24. Representation of the longwall mining district with the shearer control system**

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 25, Figure 26, Figure 27).

The obtained results are summarised in Table 1 for longwall 841A of the Bielszowice mine, Table 2in for longwall Bk-95 of Coal Mine Velenje, and in Table 3 for longwall Z-11A of the Jankowice colliery.

**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** | |

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 25, Figure 26 and Figure 27 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).

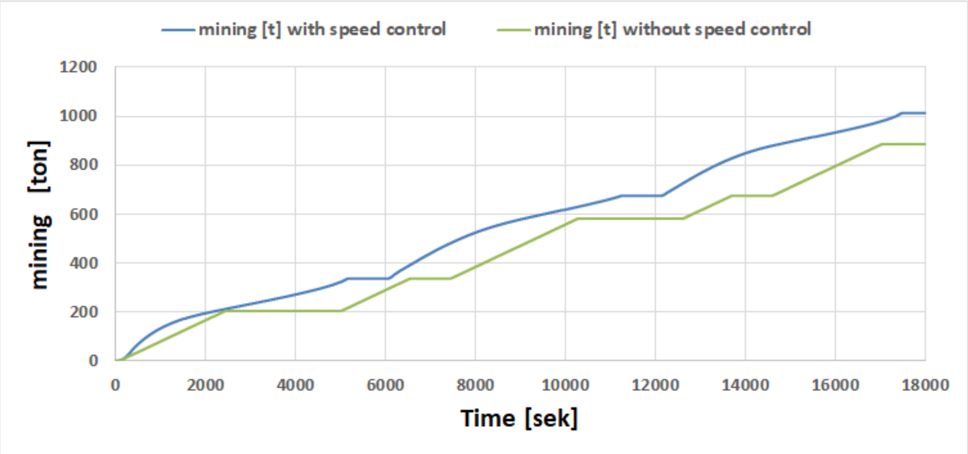


**Figure 25. Mining output (tons), Bielszowice longwall 841A**

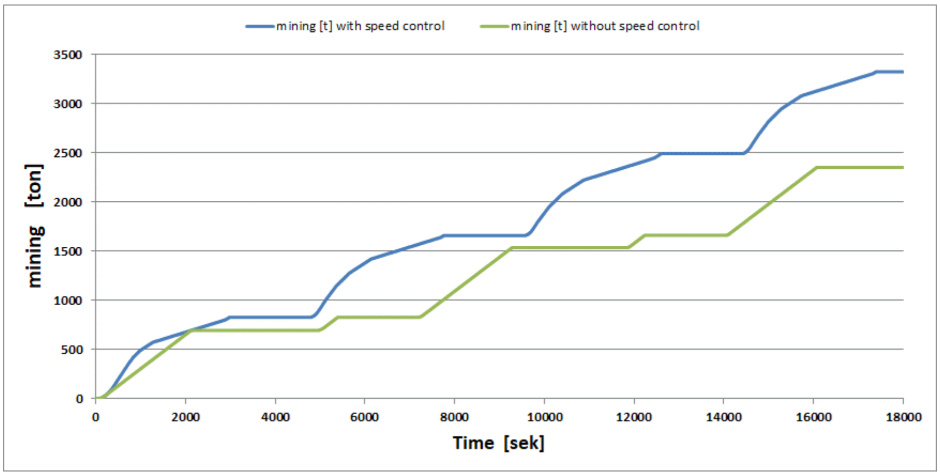


**Figure 26. Mining output (tons), Velenje longwall BK-95**

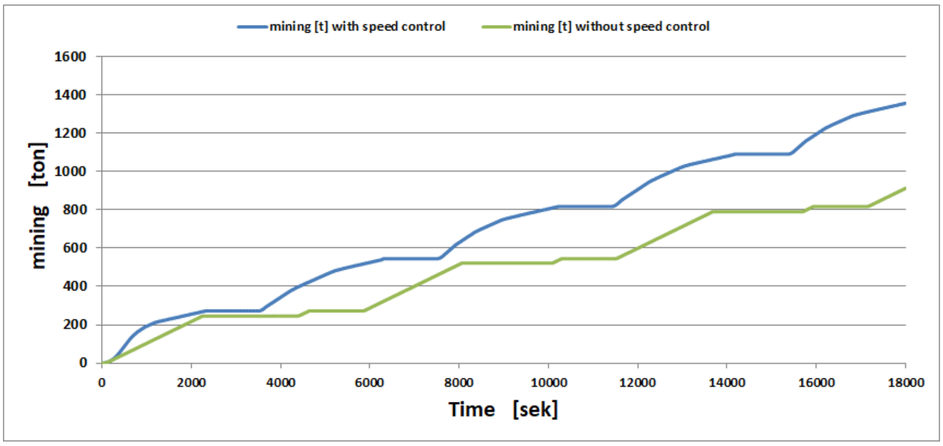


**Figure 27. Mining output (tons), Jankowice longwall Z11A**

The following Figure 28, Figure 29, Figure 30 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).

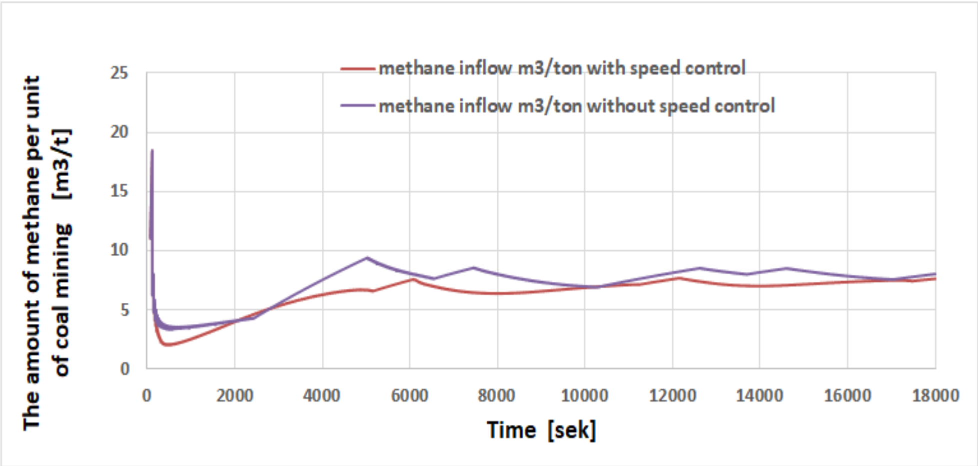


**Figure 28. The amount of methane flow per unit of coal mined, Bielszowice longwall 841A**

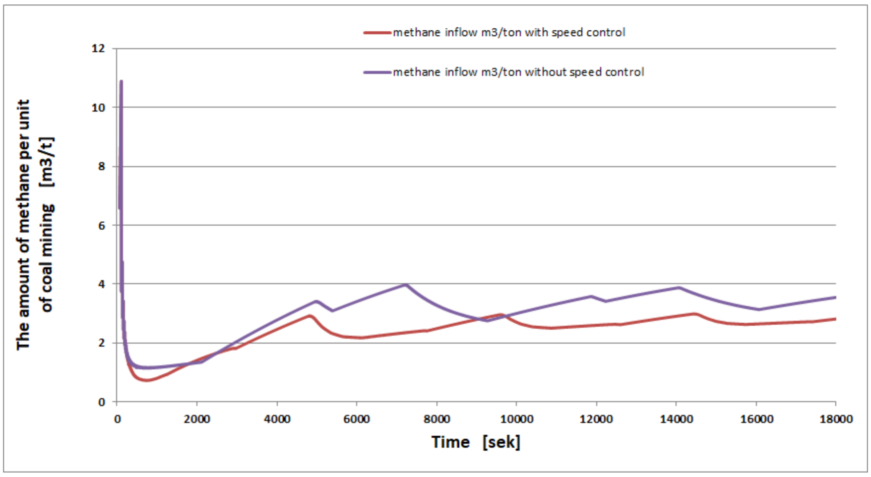


**Figure 29. The amount of methane flow per unit of coal mined, Velenje longwall BK-95**

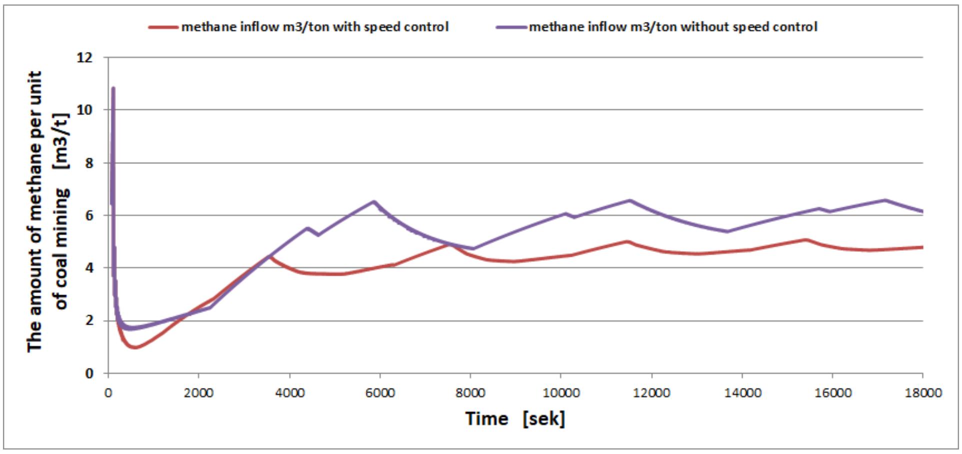


**Figure 30. The amount of methane flow per unit of coal mined, Jankowice longwall Z11A**

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.

# 8. 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. .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.

This general knowledge is supported by results of the data analyses shown in the multiple analyses of the mine monitoring data 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. First of all, simulations on calibrated models 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 virtual longwall model depend on a number of adopted parameters, and the selection of parameters of the control regulator itself is of particular importance.

In paralell with the Virtual model develoment a vast number of the field data analysis and numerical modeling led to the recommnedations for the locations of control system methane sensors. Presented simulations corresponded to current practice, which 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. Review of all the findings in PICTO 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 and over the path of the shearer as possible .

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.

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# 10. GLOSSARY

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

**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].

**Effector** - the system transforming the output signal of the regulator into the control value for the plant

**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

**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 capability including simulation of transients caused by gas emission, outbursts and undeground fires with optional escape ways management module

**VentGraphPlus** – a version of the Ventgraph Mine Ventilation Network Simulator developed at the IMG-PAN with functionality extensions including filtration in adjacent goafs.

**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

# 11. LIST OF FIGURES

## 12. LIST OF TABLES