Framework for ergonomic design of control centres in underground coal mines—A Serbian experience

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Abstract

We present a framework for solving the problem of functional compatibility between process control equipment in control centres at underground mines and operator capabilities. The equipment incorporates displays of current ventilation, gas, and fire hazard data, status of alarm and early warning systems, a voice communication subsystem, and facilities for recording and printing of data and reports. The layout of the existing control panel is compared with a recommended design. The basic principles of ergonomic design and arrangement of the controls and indicators, as well as ease of use, type of operations carried out with these controls, and operators' viewing angles are discussed. The objective is to improve the usability of control panels, display boards, and graphic screens so as to enhance the functioning of control centres and optimize control of technological processes in coal mines.

Keywords

ergonomic design, control centre, control panel, coal mining

Introduction

Underground coal mining is conducted in harsh conditions with ever-present risks of fire and explosion, toxic gases, mine collapses, flooding, and similar hazards. However, coal production from underground mines is increasing with the expansion of existing operations and opening of new ones. This has led to research into ways of detecting and quantifying hazardous conditions, as well as registering, communicating, processing, displaying, and storing the related information, automation of the mining process, and communication between employees on the surface and underground.

Previous studies in this area have included injuries in the underground coal-mining environment (Stojadinović et al., 2011), causes of accidents involving mining equipment (Dhillon, 2010; de Rosa and Litton, 2010; Kirsch, Shi, and Sprott, 2012), the underground environment and ventilation (Li and Long, 2011; Witrant et al., 2010; Yang et al., 2010), the development of methods for detecting and measuring underground environmental parameters (Grozdanovic and Bijelić, 2018; Stojiljkovic, Grozdanovic, and Marjanovic, 2014), mining equipment safety (Zeng and Wang, 2010), electrical-related mining mishaps and lessons learned (Abdalla, Kizil, and Canbulat, 2013), human factors in the design of safer mining equipment (Grozdanovic and Janackovic, 2016; Horberry et al., 2013; Horberry, Burgess-Limerick, and Steiner, 2016; Lynas and Horberry, 2011), human reliability analysis (Kovacevic et al., 2016; Tu, 2016), research and development of remote control systems (Grozdanovic, Savic, and Marjanovic, 2015; Grozdanovic, Marjanovic, and Janackovic, 2016; Grozdanovic and Bijelić, 2018; Marjanovic et al., 2016; Wang, Wang, and Pei, 2013), and communication systems (Ranjan, Sahu, and Misra, 2014).

The first generation of process control devices in Serbia, comprising a remote control system for ventilation, gas and fire parameters (OLDHAM), and alarm and voice communication systems, was commissioned in 1983 at Aleksinac coal mine. A second-generation system (DKP-1), produced by EI Institute, was commissioned in Senje coal mine in 1984. This was followed in 1988 by a new, intrinsically safe digital multiplex system (EI SM-64) at Senje coal mine in 1988. The same type of system was installed in the Soko and Ibar mines of the Rembas complex.

There were no clearly defined criteria for ergonomic considerations when these control centres were designed, so little attention was given to functional and ergonomic demands. More research on compatility between operators and process control elements in these centres is therefore required. A completely new approach to human operator's activity requires comprehensive study, since even a small error can lead to an accident, breakdown, or even destruction of the entire control system with catastrophic consequences.

An optimized operator-equipment interface is essential in a control centre. Operators are required to maintain high levels of concentration and attention, and also to have immediate control of information displays showing many different types of data, since they are required to continuously comprehend the state of the system.

Investigations of control rooms in coal mines in Serbia have identified several key factors pertaining to their ergonomic design (Grozdanovic, Savic, and Marjanovic, 2015), leading to the formulation of a new integral control model that can be applied in the mining, railway, and electrical power industries in Serbia (Grozdanovic and Janackovic, 2016) and which influenced the development of an informational system for monitoring the impact of underground coal mining on the environment (Stojiljkovic, Grozdanovic, and Marjanovic, 2014).

The functional compliance and efficiency of process control in Serbian coal mines has received increased attention since it was realized that this is not just a matter of human competence and efficiency, but rather a complex human-control interface problemc with far-reaching consequences that requires a comprehensive diagnostic and prognostic evaluation of actual and expected situations in control centres. A systematic approach based on multidisciplinary principles is therefore necessary.

Methodology

Control centres

The process control system in the Rembas mine complex covers four pits – Senje, Strmosten, Jelovac, and Pasuljanske livade, with the main control centre (CC) located in Resavica. There are two transit CCs, one in Vodna for the Strmosten and Jelovac pits and one in Senje. Pasuljanske livade is directly connected to the main CC.

This layout is based on the fact that all pits are connected with Resavica by undercuts and are located such that is possible to monitor all data from one main CC. Thus only the main CC needs to be continuously manned, which significantly reduces the number of employee working on ths system. Each transit CC is equipped with a central unit connected with the pit's substations, from which it gathers the current readings. The central unit displays current and alarm data, supports an alarm data printer and communication with the control panel and alarm-voice communication system and main CC and other necessary equipment. Transit CCs are without operators, but they provide a complete overview of conditions in the pit and when an incident occurs, operators can access these centres and take the necessary actions.

Equipment in CC Rembas (Figure 1) provides a continuous display of current readings for all ventilation, gas, and fire parameter and the states of the alarm-voice communication subsystem (AVS), early warnings and alarms for all parameters and AVS elements, records all current and alarm data, printouts of alarm data and reports on processed data (diagrams, tables, alarm figures). Equipment consists of:

- A control panel with main and backup computers R1 and R2, AVS keyboard for each pit, equipment for recording AVS conversations during alarms, two 19-inch colour monitors, a touch-screen monitor (system monitor), alarm printer for the whole system, report printer, keyboards for R1 and R2, alarm printer for Pasuljanske livade.
- Display board for each pit.
- Process computer IRI-2, multichannel intrinsically safe interface Ei SNM-64 used for conducting all intrinsically safe digital and voice communication between the main dispatcher centre and transit centres; other necessary equipment.

The overall structure classifies this system as a multi-hierarchical distributed computer integrated system (DCIS). Computer R1 works in real-time mode. Process computer IRI-2 supports all communications within the system, and functioning of the touch-screen monitor and printer for automatic printing of all alarm data. In normal conditions the R2 computer performs offline data processing, which includes the following functions:

- Receiving and archiving data from R1, and analysis of received data
- Creating shift reports in the form of diagrams and tables, displaying and printing reports
- Making modifications to the mine's linear schemes and sending these to R1 so that they can be used in the real-time mode
- Making modifications to location plans of measurement sensors and speakers installed in the pits, and sending the current location plan to R1
- Monthly data archiving, drafting of paperwork, working in real-time mode in case of an R1 computer failure.

The AVS subsystem provides:

- Communication to or alarming of any number of underground or surface communication units connected to the subsystem
- Simultaneous alarming of one or more communication units and operators' communication with one or more communication units
- Voice communications from the pit during an evacuation alarm
- Automatic broadcast of standard messages for two hazard levels and variable messages, depending on conditions in the pit

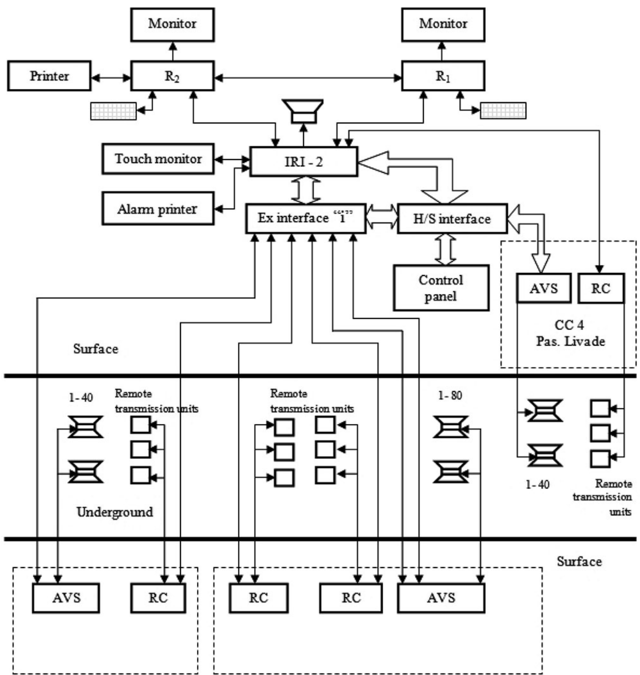


Figure 1—Process control system block diagram – Rembas mine complex, Resavica

- ➤ Communication with employees in the pit within 50 m of a communication unit
- ➤ Automatic recording of alarm situation conversations
- ➤ Control panel remote controlling
- ➤ Connection to computer systems
- ➤ Charging of local energy sources in communication units from central location.

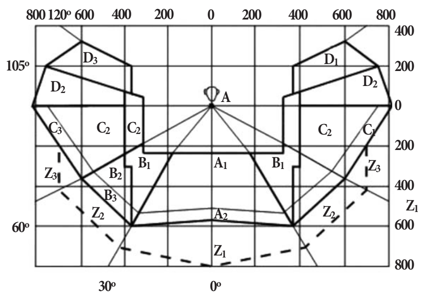
Ergonomic recommendations for control panels

An ergonomic analysis of a control panel begins with a comparison of the parameters of the existing panel with recommendations. The basic principles of ergonomic design of control panels and of arranging the controls and indicators, as well as the terms of use and type of operation with these controls (Figure 2), are as follows.

- ➤ Controls and indicators should be arranged taking into account: priority of use and grouped into logical sections, with appropriate interconnections and relationships between indicators and controls.
- ➤ Grouping of indicators and controls should be done by three principles: functionality (grouping based on function, sequence of use (grouping according to sequence of work tasks that are performed), and importance (the most important indicators and controls are placed in the optimal zone, alarm indicators are easily accessible but not within the optimal zone, and periodically used elements are placed in non-optimal zones).
- ➤ The accuracy and speed with which operators can identifying indicators and controls should be established, as well as the simplicity of manipulating these controls. Reading errors and their influence on task execution should be identified.
- ➤ Indicators must be clearly visible from the operator's position. The most important indicators must be easily recognizable, and there must be a functional interaction between the indicators and controls that they are connected with. To facilitate recognition, groups of six or more indicators should be arranged in rows or columns. Groups of 25-30 indicators should be arranged in two or three visually distinctive sections.
- ➤ Symbols for labelling indicators or controls should be simple, distinctive, and indicate the function of the indicator or control. A unified design scheme should be used.
- ➤ Control panels should be non-reflective and not include features that do not contribute to work functionality, The most appropriate colours are light grey, blue-grey, yellow, or dark grey. The dimensions for work in a seated position must not be less than 600 mm in height, 400 mm in depth (at knee level, 600 mm in depth (at floor level), and 500 mm wide.

When it's necessary to have a clear view above the control panel the height of the panel for work in a seated position should not be greater than 1100 mm from the floor, and all controls should be at 600-1000 mm from the floor.

- ➤ Since many types of control panel are used in CCs, we will review some principles for arranging indicator and controls as well as their applications (Figure 2) so that we can use the previously discussed design principles to do an ergonomic assessment of an existing control panel.



Term of use and type of operation	Suggested work zones
Term of use	
Used often	A1,B1,B2,C,C2
Used not so often	A2,B3,C3,D2,D3
While working with accessories	A1,B2,B3
High reading accuracy needed	A1,A2,B2,B3
Lower demands for sharp-sightedness	C1,C2,C3,D2,D3
Type of operation	
Operating with buttons	A2,B3,C3,D3
Operating with levers	Work zone on 300 mm in front of control point A
Thumb-operated	Work zone on 50-80 mm in front of control point A
Hand-operated	A1,B2,C2,D2
Fine operations	A1,A2,B1,B2
Different types of operation	B3,C1,C2,C3,D2,D3

Figure 2—Control panel, term of use, and types of operation with signal-control elements

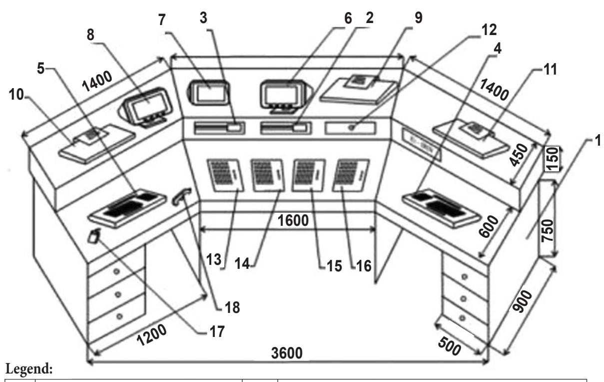
Results

The equipment in the CC of Rembas mine complex is designed to give a clear, continuous display of all ventilation, gas, and fire parameter readings and states of the alarm-voice communication subsystem (AVS), to record all current and alarm data, to print alarm data at any moment, and print reports about processed data (diagrams, tables, alarm figures etc.).

In order to perform an ergonomic analysis of the control panel it is necessary to compare the existing panel with the recommended design criteria.

The current control panel (Figure 3) is a trapezoid shape to facilitate acces to the process control elements that are placed on the sides of the panel.

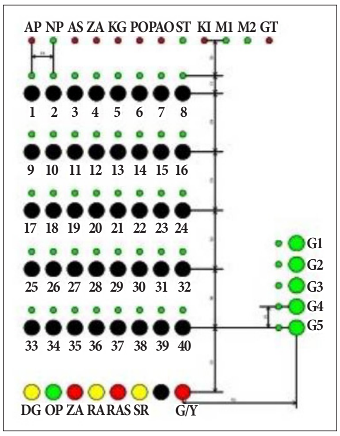
Most of the area of the operator's panel is occupied by the AVS keyboards (Figure 4). There are four keyboards in total, one for each pit, each measuring 400 × 270 mm.



Legend:

1.	Command pulpit	10.	Report printer
2.	Computer R1	11.	Alarm printer for Pasuljanske livade mine
3.	Computer R2	12.	Sound alarm reset
4.	Computer R1 keyboard	13.	AVS keyboard for Jelovac
5.	Computer R2 keyboard	14.	AVS keyboard for Strmosten
6.	Computer R1 19"	15.	AVS keyboard for Senjski rudnik
7.	TOUCH screen	16.	AVS keyboard for Pasuljanske livade
8.	Computer R2 19"	17.	Mouse
9.	Control and management system alarm printer	18.	Phone

Figure 3—Control panel at Rembas mine complex



Signal marks in keyboard upper row		
AP	Alarm call for the mine	Red color
NP	Normal call for the mine	Green color
AS	Alarm situation	Red color
ZA	Alarm activated from the control center	Red color
KG	Voice communication failure	Red color
PO	Circuit breaker failure	Red color
PAO	Automatic circuit breaker failure	Red color
ST	Pushed button	Green color
KI	Isolation fault	Red color
M1 and M2	Tape recorder 1 and 2	Green color
G/T	Main/pit	Red color
Speaker switch marks		
1-40	Speaker switches with green LED above them	Black color
Buttons and switches marks in bottom of the keyboard		
DG	Dispatcher speaking	Yellow color
OP	Ordinary call from control center	Green color
ZA	Activating alarm from control center	Red color
RA	Alarm reset	Yellow color
RAS	Alarm situation reset	Red color
SR	Recording of conversation	Yellow color
G/T	Main or transit center working	Red color

Figure 4—AVS (alarm-voice communication subsystem) keyboard for one pit

Switches, buttons, and signal indicators on the keyboard are divided into four functional groups. Indicators are located on the upper section of the keyboard; switches that activate the in-pit speakers are located in the middle (largest) section, and buttons for executing certain system functions in the lower section; switches for simultaneous transfer of information from the CC to the designated speakers in the pit are located in the right-hand lower middle section of the keyboard.

Analysis of the operator's interaction with the keyboard revealed the following.

- ➤ The layout of signalization, switches, and buttons corresponds to the ergonomic recommendations. These are arranged in four logical groups, there are clear connections between signalization and controls, and the priority of use principle is followed. Labelling is clear. The keyboard is easy to use, and errors while using it are rare. In normal situations keyboard errors do not have a significant influence on the system's functionality. In an alarm situation errors are nore serious and can have an impact on functionality of the control panel as a whole (for example, if the RAS button is pressed in error this will turn off the tape recorder, which is not permitted in an alarm situation). The indicator layout does not correspond to ergonomic recommendations – the 12 indicators should be grouped into two rows.
- ➤ The spacing between adjacent switches or buttons is 18 mm, whereas the ergonomic recommendation is 22 mm.
- ➤ The black colour of the speaker switches does not comply with ergonomic recommendations; they should be white or blue. Colours of the rest of the switches and buttons and all the indicators are according to recommendations.

Ergonomic analysis of the control panel was conducted by measuring, analysing the layout of signal-control elements on the centre and side sections, checking the colour type and comparing the results with the ergonomic recommendations.

The panel's dimensions are: height of horizontal part 750 mm; depth at knee level 600 mm; depth at floor level 900 mm; frontal part width 1600 mm. These dimensions correspond to the ergonomic recommendations. However, the shape of the panel is not compliant since most of the right-hand side is out of reach when the operator is seated.

The layout of elements in the centre and side sections was analysed by comparing the data gathered (Figure 5) with the recommendations for terms of use, type of operation, and work zones (Figure 3).

By applying the terms-of-use principle to the keyboards three groups of switches and buttons can be identified: frequently used (buttons DG and OP and switches 1-40); used in alarm situations (buttons ZA, RA, RAS and switches 1-40); rarely used switches (G/T, SR, and G1- G5).

Compliance of these terms of use with recommended work zones depends on compliance of keyboard T1-T4 positions on the panel's front section with recommended work zones. Keyboards T2 and T3 are positioned in appropriate work zone A. Parts of T1 and T4 keyboards located in zone B are outside the recommended range of 0-600 mm. Keyboard T1 should be moved 150 mm to the right and T4 100 mm to the left.

The R1 computer keyboard in zone C is outside of the recommended range of 0-800 mm and is thus not compliant with ergonomic recommendations. The keyboard of the R2 computer on the left side of the panel, which functions automatically as a backup in the case of R1 failure, is not positioned according to ergonomic requirements.

As regards 'type of operation' criteria, all switches and buttons are push-type.

The white colour of the panel corresponds with ergonomic recommendations.

The above analysis clearly shows that ergonomic recommendations were not taken into account when designing this control panel.

In the CC of Rembas mine complex, data is displayed on three graphic screens: the 19-inch colour monitor of computer R1, with 1230 × 860 resolution, which shows information in real time; a touch-screen monitor, displaying information based on functional demands; and the 19-inch colour monitor of computer R2, with 1230 × 860 resolution, which shows diagrams and tables that are generated offline by computer R2.

All three monitors are located on the panel's rear section, which is 400 mm wide and extends 150 mm above the front section of the panel (see Figure 3). From an ergonomic point of view, the R1 colour monitor and the touch-screen monitor are especially interesting since they display both current and alarm data in real time. Measurements in the CC reveaked that:

- ➤ The distance (L) between the R1 monitor and dispatcher's eyes is 1050 mm
- ➤ Size of the symbols for labelling process control devices (S) is 5 × 5 mm
- ➤ The symbols for marking the mine galleries, current measurents, and alarm data and device numbers measure 5 × 3 mm
- ➤ Angles of vision are determined from Figure 5 and the following formula:

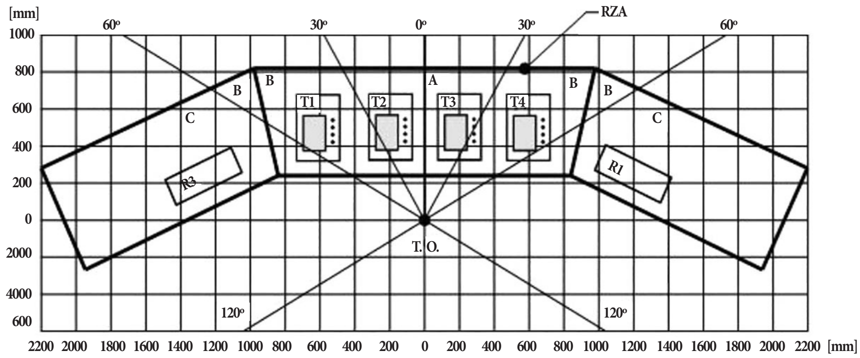


Figure 5—Control panel work zones

$$\alpha = 2arctg\frac{S}{2L} = 2arctg\frac{0,5}{2\cdot 1.05} = 16,32' \quad [1]$$

For our conditions where precise readings are required, angle α should be 35-40'. It is obvious that ergonomic recommendations were not considered when this information display was installed.

The distance (L) at which the colour monitor should be situated so that the operator can quickly and accurately read the necessary symbols or alphanumeric values is calculated by the following formula:

$$L_{\max} = \frac{S}{2tg\frac{\alpha_{\min}}{2}} = \frac{0.5}{2tg\frac{35'}{2}} = 49cm \quad [2]$$

The correct distance can be realized by placing the colour monitors right on the edge of the panel's raised front section

The same conditions apply to the touch-screen monitor since sign height (S) and distance (L) are the same. The construction of this monitor does not allow it to be moved in order to provide a 35' angle. This can only be achieved by modifying the panel. We will calculate the distance L that will allow the operator to obtain the precise reading, but not quickly. Angle α for this situation, according to the recommendations, is 18' to 20'. For distance L we obtain:

$$L = \frac{S}{2tg\frac{\alpha_{\min}}{2}} = \frac{0.5}{2tg10'} = 86cm \quad [3]$$

In the present situation there is room to move this display forward by 19 cm.

The colour scheme used on the real-time information display is compared with the recommended colours in Table I.

Table I

Colour scheme for real-time information display

	Colour used	Recommended	Compliant
Background	Dark blue	Dark	Y
Mine tunnels	Red, blue[1]	-	-
Normal conditions	Light blue	Green	N
Early warning	Dark blue[2]	Yellow	N
Alarm	Red[2]	Red	Y
Total colours	5	3-7	Y

[1]In underground coal mines worldwide red is used to denote an inlet air flow and blue an outlet
[2]With blinking symbol on control device

Parameters for sensitivity and screen contrast and illumination of the workplace are not given here. It is therefore not possible to reach a final verdict on the quality of the information display. However, it's obvious that the colours were not chose based on ergonomic recommendation.

In underground mines the location of work sites is constantly changing, and thus control instruments also have to be moved. These changes must be updated in the remote control system in order to obtain the correct data. However, updating these changes on the display board is often forgotten. This troubles the operators, as was pointed out in interviews conducted with them. These boards enable the CC operators to view the layout of control instrumentation inside the mine, the dimensions of the workings, diagrams of parameter changes, and to obtain a realistic picture of the environmental conditions in the entire pit. Based on this analysis, important data is gathered, such as the locations where methane may accumulate or spontaneous combustion occur, and the condition of the ventilation system. For example, when an accident occurred in Soko mine in 1998, by using the display board, together with data about the location of the explosion and the timing and location of damage to the ventilation doors, it was calculated that the speed of the blast after the methane explosion was around 300 km/h. Boards are placed behind and above the monitors on the CC wall or on separate stands at a distance appropriate for the operator. These boards are of great value and should be updated regularly to reflect changes inside the pit and should be improved. This mainly applies to improving the way of updating these boards based on the progress of mining operations and appropriate changes in process control devices layout.

Conclusion

Existing design solutions for control centres show some significant deficiencies related to: functional suitability and operator efficiency, particularly as regards the ergonomic aspects of process control equipment usage. Since there are no criteria for size and layout of equipment, and given the large number of instruments and communication devices, there are no clear guidelines for deciding which solutions to choose in order to enhance operators' functionality and efficiency.

These deficiencies are present because no research was conducted before these control centres were installed. Their combined impact poses a hypothetical 'model-problem'. Attempts to solve this problem by presenting proposals regarding optimal functional suitability and efficiency, as well as information compliance, for control centre operators will significantly improve the functioning of the entire control system.

Acknowledgments

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