Control and Management of Coal Mines with Control Information Systems

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Abstract: *This paper presents the study of control and management of technological processes in coal mines through means for displaying information. Information flow in the analysed closed systems consists of production process in an Underground Coal Mine (UCM), Computer System (CS), Display Units (DUs), Operators (Os) and Control Devices (CD). The mathematical model is applied for describing information filtering, where corresponding filtering coefficients define information flows. The framework for the O-computer dialogue presents the basic principles of the dialogue between the O and means for displaying information. It defines the amount of information displayed, dialogue characteristics, dialogue processes and the mathematical model that describes information flow.*

1. Introduction

Although different methods of coal mining have been developed, the risk of accidents in Underground Coal Mines (UCM) still remains, making the underground mining one of the most dangerous occupations [3, 4, 14]. The complex environment with bad working conditions, the mining and transportation equipment and the existence of flammable gaseous affects the safety performance in Serbian coal mines.

To achieve higher level of safety, at the beginning of the nineteen-eighties, the Control Centres (CC) started being introduced in Serbian coal mines with underground exploitation. Their main purpose was to centralise the control of mine working environment, with the possibility of later upgrading with additional functions.

Chronologically speaking, process Control Devices (CD) in Serbian coal mines evolved in the following manner. The first generation, the remote control system for ventilation, gas and fire parameters (Oldham) and alarm and voice communication systems was introduced in 1983 in Aleksinac mine ("Morava" pit). Presentation of information was carried out on the display panel and data recording was achieved using multi-channel printer. The Operators (Os) monitored the condition of mine working environment based on signals and instrumentation on a display board. Management of underground mines through such means for displaying information was limited (the number and type of presented data). Data from mine pits came directly to the display panel, almost without any additional processing.

The second generation was the Remote Control Station 1 (RCS-1) produced by EI R and D Institute and introduced in Senje coal mine in 1984. The third generation was the new remote control system, intrinsically safe digital multiplex system EI SM-64, which was installed in Senje coal mine in 1988. The same type of the system was later installed in Rembas mine complex, Soko and Ibar mines [28]. The Control Information Systems (CIS) installed in these mines is described in this paper.

The paper is organised as follows. This section is an introductory section, where the development of the CIS in Serbian UCM is described. Section 2 presents the literature review. The underground coal mine process control system is described in section 3. Section 4 presents the mathematical model of information filtering and the dialogue between the *Os* and means of presenting. The last section consists of concluding remarks.

2. Literature Review

The complex environment of an underground coal mine requires the environment, devices and miners to be constantly monitored to ensure safe working conditions during coal production. A typical CIS is based on three-level architecture, consisting of sensors, substations for location and communication purposes, and CC [9, 33, 36]. The system provides the data on current situations in mine pits, as well as the data on the production units, ventilation, communication and personnel. Gas explosions are major causes of accidents in UCM and atmospheric monitoring systems detect atmospheric conditions in underground locations [11, 38].

The development and use of CIS is analysed throughout the lifecycle, where access privileges can be described by use cases [2]. In classical systems, a wired serial communication enables high data rate transfer. The problem exists during the emergencies, when alternative channels of communication are needed. In order to increase the scalability and reduce the maintenance costs, wireless sensor networks have been introduced [5, 9, 24, 37].

There were no clearly defined ergonomic requirements during the design of the CC in Serbian coal mines. Therefore, it was necessary to make a more comprehensive research on compliance between the *Os* and process control elements in these centres [13]. Completely new structure of the *O's* activities required more comprehensive study and research, since even a small error could lead to an accident, breakdown or even a destruction of the entire control system, with catastrophic consequences for humans and the environment [12].

The importance of the human factor in process industries is rather underestimated. The human factor is usually missing in process safety analyses, as stated in [6, 26]. The importance of the human factor and ergonomics is described in [17]. The human element in the control systems is important in order to achieve optimal control system performance. That is especially important in industries characterised by the occurrence of large accidents that can be very dangerous and with fatal outcomes (for example, nuclear power plants, air traffic control, underground mines or mineral processing) [7, 8, 15, 22, 26, 39].

In order to analyse the human factor in the control rooms, two different approaches are defined [30]. The first approach is based on effective training and selection of the *Os* as central parts of a system, whereas the second one analyses the abilities and limitations of the *Os* in the system that is developed to limit the involvement of the *O*. There are numerous factors that can affect the performance of the *Os* in the control rooms and centres, during normal activities and emergency situations. These factors can be, among others, factors of human-machine interface, the *Os* knowledge and training and communication procedures.

The precision of decision making of the *Os* is influenced by the information they receive. Conventional control rooms are based on analogue instrumentation and the control systems. Modern control rooms are based on digital presentation equipment and the control systems. Many case studies from different mining and minerals processing sectors are based on 'Naturalistic Decision Making' theory [16]. Removing human from the decision making loop by means of automation is proposed as the solution for increasing the reliability of a system, but the *Os* must stay in order to control the operations and initiate adequate safety activities [31]. Therefore, different interactions between the *Os* and equipment for monitoring and control in the control rooms are needed [23]. Human-centred design principles for interactive systems are also applied and desirable [19].

Many ergonomic principles are applied in the design of work systems [20]. Ergonomic design principles of the CC are described in [18] in detail. Principles of the control centre design, such as the control room layout, layout and dimensions of workstations, displays and controls, as well as the principles for the evaluation of the CC are defined in this standard class. The development of the control rooms oriented towards the efficiency of the *O's* activities is the key factor of success of monitoring and control processes.

The *O* gets a lot of information from the process. It is not possible to focus on all available variables at the same time. Standard interface consists of a great number of LCD panels (displays and monitors). Focusing on the right data is very important, in order to be able to make appropriate decisions just in time [32]. New devices are developed to simplify communication between the *O* and the machine and the most important aspects of human-machine interface are colours, text presentation and audio effects [10, 35]. User interfaces are sometimes unique or very complex and special structural metrics is needed for evaluation [1].

Design and operation of modern control rooms and the *O's* workload influence the reliability of the *Os* [21]. The design of the CC, where the human *O* is the central point, is also important, especially in interactive systems [19]. High mental workload has a significant impact on the quality of the *O's* performance [29]. Information presented to the *O* must be of a manageable quantity; otherwise, the risk of mistakes would be increased. The way in which human controls a process is defined by received and interpreted information from processes, delivered in the control room [8, 25].

3. Description of the System

In modern coal mine CC, information is displayed on colour video display terminals as shown in Figure 1.

Figure 1. The control centre in rembas mine complex.

The amount of information received by the *O* is significant. The increased amount of information means that it is important to extract important

information from less important information, i.e., to perform information filtering. CIS are the basis for efficient centralised mine management as shown in Figure 2. During the functioning of the CIS, information is collected and the *O* is notified about all changes.
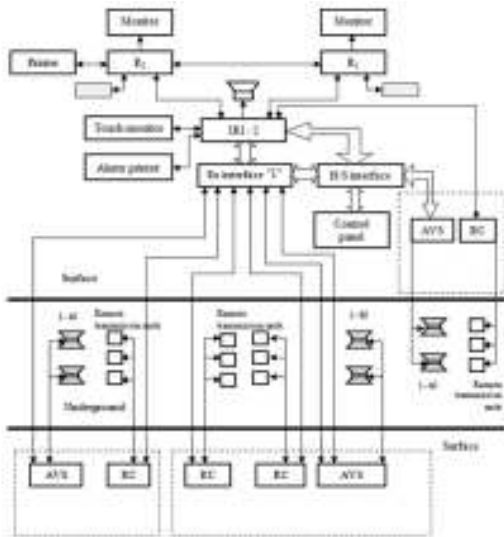

Figure 2. Process control system block diagram rembas mine complex, resavica.

Equipment in CC consists of the control panel and the following components: Main and back up computer (R1 and R2); AVS keyboard for each shaft; equipment for recording AVS conversation during alarm; two colour monitors; touch screen monitor (system monitor); alarm printer for the whole system; report printer; keyboards for R1 and R2; alarm printer for "Pasuljanske livade" mine; display board for each pit; IRI-2 process computer and 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.

Computer R1 works in real-time mode. Process computer IRI-2 supports all communication within the system and functioning of touch screen monitor and printer for automatic printing of all data about alarms. In normal conditions, R2 computer performs off-line data processing, including data archiving and special analyses.

R2 computer's program has the following options: Receiving data from R1 and archiving it on R2; analysis of received data; making shift report in the form of diagrams and tables; report displaying and printing, making modifications in mine's linear schemas and sending these schemas to R1 computer so that they can be used in real time mode; making modifications in location plans of measuring devices and speakers installed in pits and sending the current location plan to R1 computer; monthly data archiving; drafting of paperwork and working in real-time mode in case of R1 computer failure.

CIS provides a range of options for the *O*: Presentation of the most important information in a given situation, as well as various calculations, rating information, repetition of past data and events, information filtering and prediction of future events.

The theory of information filtering is applied because all information coming from UCM is presented on the Display Unit (DU) and does not require the *O's* response. In other words, the *O* must respond only to the relevant information from the UCM, take necessary actions by means of the CD and ignore irrelevant information [34].

In modern computer integrated mining CIS, information display is performed on display panels and colour monitors. The content of displayed information is created by the Computer System (CS). Hence, the dialogue between the *O* and the system for displaying information actually means the interaction between the *O* and the CS, as well as the analysis of efficiency of this interaction. What the CS is expected to present to the *O* defines the content of information displayed on the screen. What the *O* needs to enter into the CS is presented in the form of images or text on the screen and then transferred to the CS. In this way, the continuous dialogue between the *O* and means for displaying information or between the *O* and the CS is realised. Modern CIS, which, in addition to monitoring and control, have functions of analysis, process optimisation and design and management support, have more colour monitors that work as workstations in integrated CIS. Workstations are workplaces on independent locations, connected to network and using resources of the CS. Simultaneous work of several workstations is possible. One of the resources of the CS is the database that consists of various types or classes of data for different users [27].

4. The Model and Results

4.1. Mathematical Model of Information Filtering

In coal mine CC, display panels are used as well for information presentation. Display panel presents a linear scheme of mine ventilation system with clearly marked routes, areas that are separately ventilated, positions of ventilation doors, transportation routes, power facilities and distribution systems, positions of water collectors and drainage pathways, because the size of colour monitor is not enough to clearly display all data for unique needs of different users.

Figure 3 shows information flow from UCM to the CS, the DU, the *O* and the CD. In presented configuration of CIS, colour monitor DU1 and display panel DU2 are used for information presentation.

In Figure 3, r_{X-Y} presents information flow from one part of the system to another, whereas f_Z is the information filtering coefficient.
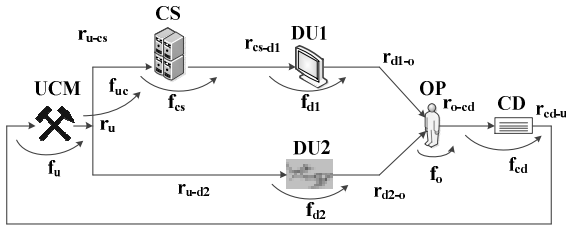
Figure 3. Information flow in CIS containing CS, DU1 and DU2.

Figure 4 presents work zones on management console used as CD. Figure 5 shows information presented on DU1. Figure 6 shows the information presented on DU2.
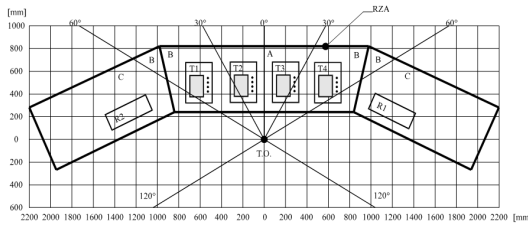

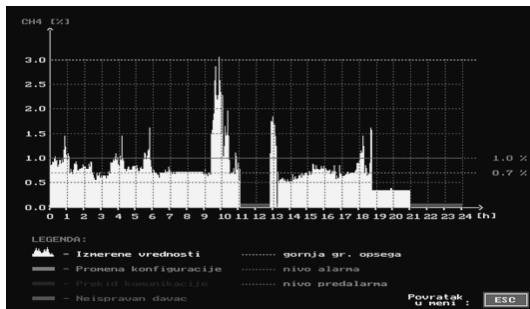Figure 4. Work zones on management console.
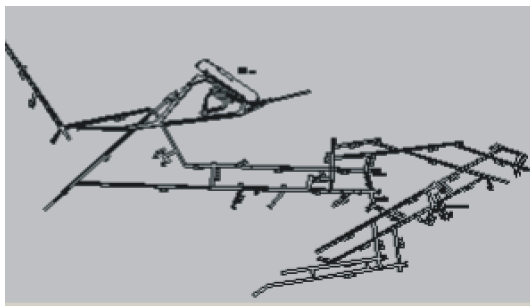

Figure 5. Data presented on DU1.

Figure 6. Data presented on DU2.

For the analysis of information flow in this system, theory of information filtering is used. The filtering coefficient for the *O* is defined as follows:

$$f_o = r_{o\text{-}cd} / r_{ot} \qquad (1)$$

Where

$$r_{ot} = r_{d1\text{-}o} + r_{d2\text{-}o} \qquad (2)$$

And the *O*'s maximum burden occurs in the situation when the *O* responds to all information displayed on the DU by means of CD. In that case, $r_{ot} = r_{o\text{-}cd}$ and $f_o = 1$; this situation is not realistic, but only possible in theory. The value is in the range of $0 < f_o < 1$.

Other filtering coefficients are calculated in the same manner. For the purpose of further analysis, we take the value $r_{o\text{-}cd} = r_{cd\text{-}u}$, that is, $f_{cd} = 1$.

After applying the theory of information filtering, the following terms are obtained:

$$r_{d1\text{-}o} = f_{d1} \cdot r_{cs\text{-}d1} = f_{d1} \cdot f_{cs} \cdot r_{u\text{-}cs}, \qquad (3)$$

$$r_{d2\text{-}o} = f_{d2} \cdot r_{u\text{-}d2} \qquad (4)$$

Taking into account that the information is transferred to both DU, DU1 and DU2, it follows that:

$$r_{u\text{-}cs} + r_{u\text{-}d2} = k \cdot r_u. \qquad (5)$$

For $k=1$, Equation 5 becomes $r_{u\text{-}cs} + r_{u\text{-}d2} = r_u$, which means that information is transferred to DU1 or to DU2; for $k=2$, Equation 5 becomes $r_{u\text{-}cs} + r_{u\text{-}d2} = 2r_u$, which means that all of the information from the process is transferred to both DU, DU1 and DU2.

If $1 < k_o < 2$, Equation 5 becomes:

$$r_{u\text{-}d2} = (k - r_{u\text{-}cs} / r_u) \cdot r_u = (k - f_{uc}) \cdot r_u. \qquad (6)$$

The overall information flow to the *O* (r_{ot}) is equal to:

$$r_{ot} = r_{d1\text{-}o} + r_{d2\text{-}o} = f_{d1} \cdot f_u \cdot f_{uc} \cdot f_{cs} + f_{d2} \cdot f_u \cdot (k - f_{uc}) \qquad (7)$$

According to Equation 1, after simplifying the expression, we obtain the information filtering coefficient via the *O* f_o:

$$f_o = 1/((f_{d1} \cdot f_{cs} \cdot f_u \cdot f_{uc} + f_{d2} \cdot f_u \cdot (k - f_{uc})) \qquad (8)$$

Activities of the *Os* can be divided into two phases. When something happens, information is transferred through $r_{d1\text{-}o}$ about that event only. The main data flow occurs through $r_{d2\text{-}o}$, which enables displaying actual situation to the *O*. Until the *O* receives information about the actual state, he or she does not take any activity.

4.1.1. Managing Information Flow by Means of Filtering Coefficients

The coefficients f_{d1} and f_{d2} filter irrelevant information, while the coefficient f_{cs} filters relevant information. Programming of the CIS can define that the coefficient f_o is within the specified range. CIS accepts all the information, regardless of the speed at which it is generated. The *O* selects the information presented on the DU, in order to see and process it. In this way, the total amount of information is split into small quantities of information, which the *O* can process all at once. In this way, the *O* can extract relevant from irrelevant information.

The value of the coefficient f_{cs} ranges between 10^{-1} and 10^{-3} and this coefficient can filter out large information flows, because the program can determine in advance the information needed for the normal operation.

The flow $r_{d2\text{-}o}$ is equal to:

$$r_{d2\text{-}o} = r_{u\text{-}d2} \cdot f_{d2} = f_u \cdot f_{d2} \cdot (k - f_{uc}) \qquad (9)$$

In case the system presents information only on display plate, it becomes:

$$r_{d2-o} = f_u \cdot f_{d2} \qquad (10)$$

It can be seen that the expression 9 is in fact the expression 10, multiplied by factor k-f_{uc}.

Previously, it has been taken that $1<k<2$, which shows that:

$$0<f_{uc}<1 \qquad (11)$$

It follows that the value of the factor k-f_{uc} is in the range.

$$0<(k-f_{uc})<2 \qquad (12)$$

The real value is $(k-f_{uc})<1$, so that the value of expression 9 is always less than the value of expression 10.

The value of factor $(k-f_{uc})$ can determine the *O*'s information workload, so that no unnecessary information is presented on the display panel.

The second phase of the *O*'s activities is the selection of certain information displays on DU1, control by means of CD and then tracking the results and performance of control process on DU2.

The main *O*'s workload during the first stage of information flow is presented by means of the following equation:

$$r_{d2-o} = f_u \cdot f_{d2} \cdot (k-f_{uc}) = 1/f_o \qquad (13)$$

Since, there is low information flow from CIS. The filtering coefficient on DU2 is:

$$f_{d2} = 1/f_o \cdot f_u \cdot (k-f_{uc}) \qquad (14)$$

Figure 7 shows functional dependence $f_{d2}=F(f_{uc})$ and the diagram is drawn according to the following values: $0.05<f_o<0.2$; $f_u=10^2-10^3$; $k=1.3$.

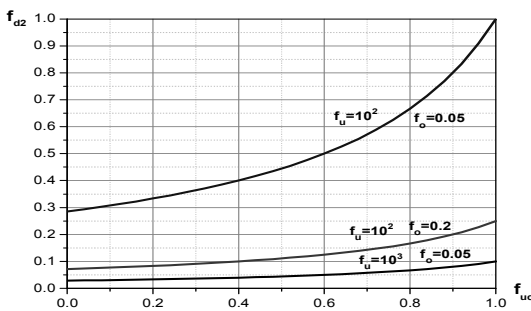
Figure 7. The functional dependence $f_{d2}= F(f_{uc})$.

Filtering of information on DU2 must be larger if the amount of information from the process increases or if small amount of information goes into the CS. The impact of f_o on f_{d2} is lower if f_u has higher value. Only for low values of f_u can f_o have effective impact on f_{d2} and the larger the value of f_{uc}, the better.

On the basis of the previous analysis, it is evident that during large-scale disturbances in the mine, the *O* should use the picture of a selected part of the mine where emergency happens, so that the bigger picture can be clearly displayed on a display panel. Display panel should not be overloaded with unnecessary information for the *O*, because that information can be easily obtained from the CS when needed.

4.2. The Dialogue between the Operator and Means of Presenting Information

The dialogue between the *O* and CS represents in fact a targeted set of actions and resources to ensure the data exchange between participants in communication in the system *O*-CS.

Generally, the goal of the interaction process may be:

- Information, which is manifested in the provision of information or documents during the dialogue.
- Management, which consists of giving advice, options or results for decision-making process during the dialogue.

During the *O*-CS dialogue, continuous harmonisation of the dialogue is performed, depending on the amount of information that is exchanged. The stated amount of information is characterised, to some extent, by the complexity of the *O*'s perception of information *C*. Regulation of *C* and individual abilities of perception may affect the efficiency of the *O*-CS dialogue:

$$C = \sum_{i=1}^{K_E} C(h_i) \qquad (15)$$

Where $C(h_i)$ is the complexity of perception of the quantity of operations by the *Os* during the ith stage of communication; k_E is the number of stages of communication. Furthermore:

$$C(h_i)= \overline{L}(h_i) \cdot I(h_i) \qquad (16)$$

Where $\overline{L}(h_i)=1- L(h_i)$; $L(h_i)$ and $\overline{L}(h_i)$ indicate accuracy (eligibility) and inaccuracy of information contained in h_i; h_i indicates the deviation from the average *O*'s perception which is determined by the perception of previous amount of information. Accuracy and inaccuracy can be expressed as a function of h_i:

$$L(h_i)= 1- h_i / a ; \overline{L}(h_i)= h_i / a ; \qquad (17)$$

Where a indicates the deviations that affect the loss of full perception of the average.

If $h_i=a$, the values are $L(h_i)=0$ and $\overline{L}(h_i)=1$. These values indicate the inability to connect the information presentation, which refers to an object and which is perceived, with the new batch of information, which differs significantly from the presentation of the object which has already been created on the part of the *O*.

Furthermore, it can be determined that when $L(h_i) \rightarrow 1$, $\overline{L}(h_i) \rightarrow 0$ $\overline{L}(h_i) \rightarrow 0$, for $h_i \rightarrow 0$, small amount of new information on object is efficiently "entered" into the system of definitions that characterises the object and that is created in the mind of the *O*. In Equation 16, $I(h_i)$ indicates the perceived amount of

information contained in the amount of messages that has a deviation of h_i:

$$I(h_i)=ln(h_i/h_0) \qquad (18)$$

Where h_0 is some value of h_i, which has a physical meaning of sensitivity threshold of the perception channel. For example, if $h_0>>h_i$, then $I(h_i)=0$, which means that the information is not perceived.

The previous analysis shows that in the process of the *O*-CS dialogue, the *O*'s perception of information is very important, as well as the efficiency of overall mutual relations between the *O* and the DU. Briefly described mathematical model can be the basis for further analyses and can allow calculations of the effectiveness of interaction between the *Os* and the DUs.

4.2.1. Structure and Characteristics of the Dialogue

For the realisation of the *O*-DU dialogue, it is necessary to develop procedures or methods of construction and organisation of the dialogue, types of systems of interaction and to define the characteristics of the dialogue. Figure 8 presents a block diagram of the interaction.
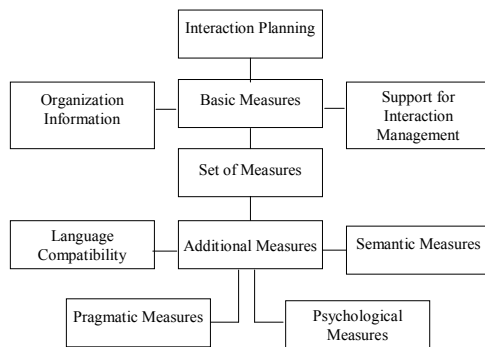

Figure 8. The measures (steps) in O-CS interaction.

Various forms of the O-DU dialogue, that is, interaction, characterise the organisation of information exchange processes. Main features of interaction are presented in Figure 9 [19].
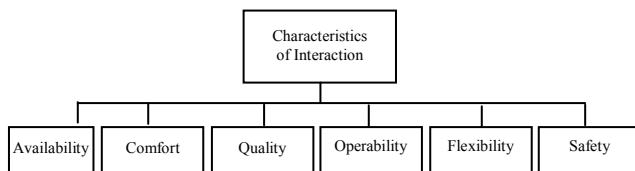

Figure 9. Characteristics of human-computer interaction.

One feature of the interaction system is availability, which is determined by:

- Possible total number of users of different classes, *n*.
- The number of classes of users allowed to work on the system, n_K characterised by the universality of the system (the ability of the system to serve broad class of users).

- The degree of simultaneous servicing of more users from various classes of users, *b*:

$$b=n'_k/n_k \qquad (19)$$

Where n'_k is the possible number of classes of users that simultaneously work on the system.

Another feature of interaction is working comfort of users, which can be determined by the degree of compliance with their needs in providing:

- Means of communication required by users (sufficient capacity of technical, linguistic and other means).
- The shortest possible response time to user's questions t_P:

$$t_P=t_R+t_o \qquad (20)$$

Where t_R is the waiting time in queue and t_o the time for question processing:

- Minimising the costs of users in the process of their preparation for the work in the system (for example, the minimisation of the time spent on preparation).
- Different types of alignment in human-CS *O*-CS.

The quality of functioning of the system can be represented by the following relationship:

$$B=1-K_K/K_E \qquad (21)$$

Where K_E presents the number of stages (steps or cycles) during the communication, whereas K_K is the number of corrective actions needed to achieve the desired result during the process of communication.

As a criterion for evaluating the *operability* of the system of interaction, the time *T* can be applied, referring to the time spent on the implementation of the system of measures in the communication process:

$$T = \sum_i T_{E_i} \qquad (22)$$

Where T_{Ei} is the time required for the implementation of the ith stage of communication:

$$T=t_{Gi}+t_{Ri}+t_{Oi}+t_{Di}+t_{Ki} \qquad (23)$$

Where t_{Gi}, t_{Ri}, t_{Oi}, t_{Di} and t_{Ki} are times for generating a question, waiting, processing questions, sending and receiving responses and corrections, respectively, during the ith stage of communication.

Flexibility of the *O*-DU dialogue is characterised by the ability to reorganise and change parameters during the dialogue, with the aim of optimal solving of the task for ongoing communication. The number and class of users (n, n_k, b) or the structure and content of the information circulating in the system may be subject to change. Flexibility in the system is achieved through the organisation of active modes of interaction, the presence of enough monitors and additional reserves in the communication system.

An important characteristic of means of interaction is safety, which is characterised by the possibility of

continuous and flawless functioning at different stages of communication. When considering the safety of human-computer interaction, it is necessary to point out the following stages of work:

- Preparation of initial information and its presentation in a form suitable for entering it into the computer.
- Entering information into the computer.
- Processing information in the computer.
- Presentation of results to the *O*.
- Receiving and processing of information by the *O*.

In accordance with this, the safety of operation of the system of interaction *H* can be determined as:

$$H = \prod_{i=1}^{5}(1 - Q_i) \qquad (24)$$

Where Q_i presents the error probability during one of the previously considered phases (*i*=1, 5) of system functioning.

5. Conclusions

In case an abnormal situation occurs in most parts of the mine, the *O* must quickly create an image of the emergency event. The image of the mine is presented on the DU as a linear scheme of mine ventilation channels, as a single figure, or as a range of figures that represent some parts of the mine. Individual images present events in some parts of the mine. The *O* lists the required information, and must remember the events and take some control actions by means of CD, based on the created image. Therefore, it is necessary that the amount of information, on the basis of which the control action is taken, is separated from the whole set of information available in CIS. It is evident that the theory of information filtering allows that information extraction.

The importance of harmonisation of the *O*-DU communication is defined by CIS functions and by tasks of the *Os* and the technical personnel resulting from their obligations to permanently control complex technological process of underground mining based on information obtained from CIS. For the *Os* using real-time information, quick perception of the presented information is very important. With respect to the technical staff, the possibility of uninterrupted use of information for their specific needs is of special importance. Therefore, the paper presented the analysis of complexity of information perception and the regulation that may affect the efficiency of the *O*-DU dialogue, as well as the characteristics of that dialogue, whose harmonisation can enable comfortable work of the technical personnel in the coal mines.

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