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THE PROBLEM OF THERMAL ENVIRONMENT IN UNDERGROUND MINING: AN INTEGRATED SOLUTION PROPOSAL USING NEW TECHNOLOGIES AND OPTIMIZATION SOFTWARE

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ABSTRACT:

This article discusses environmental conditions in underground mining (in particular, those related with thermal environment), relating them to the negative effects that they can cause in the health, safety and productivity. Aiming to identify the best operating level of a ventilation system is presented a proposal based on a quantitative model combining environmental, physical and metabolic data with ventilation control and optimization software. The combination of all these factors provides an optimized ventilation solution for implementation in the mine. It can be performed automatically and in a real time mode, for each working front through the automatic control of air flows (supplied by localized ventilation systems), with the use of a wireless communication interface between the computer (source) and the ventilation systems (receiver).

Keywords: Mining; Thermal Environment; Safety; Productivity; Energy Efficiency; New Technologies; Optimization Software.

1 INTRODUCTION

Underground mining work is considered as a high risk activity, since it is performed under extreme environmental conditions. As a result of geothermal gradient, this situation is worsened with increasing mines depth which continually has taken place. Although mining activity be filled as dangerous, the new generation of safety technology is helping protect the lives of workers (Fisher, 2011). In this context, the environmental control of workplaces conditions is a central concern of the companies operating in the sector.

However, these elements are only a part of a broader problem that companies are facing: on one hand, it is necessary to keep the pollutant levels and temperature below reference limits and, sometimes, reduce the time of human activity in the critical workplaces; on the other hand, it is necessary to maintain high levels of productivity and energy efficiency. Since the early 1900s, a relentless search has been under way for new and innovative mining technologies in order to improve health, safety, and productivity (National Research Council, 2002).

Several new technologies created a huge potential for a positive shift in the trajectory of the global mining industry. These new technologies include gathering and sharing data through cloud-based networks, using artificial intelligence in machines to reduce labor costs, biomineration solutions, portable technologies and even hybrid aircraft to transport equipment more easily to remote regions (Bailey, 2016).

This multiplicity of objectives is itself sometimes conflicting. In general, the aim is to find the balance between an ethical, legal framework and corporate social responsibility - by promoting work environments that enhance comfort and haven't a negative impact on worker's occupational safety and health - and the operational conditions at a minimum cost, in order to ensure an adequate competitive position in the marketplace (Bacaloni et al., 2018).

Based on this dichotomy, this article presents an integrated approach to address the problem. A combined use of new collecting data technologies, simulation and optimization software and also new wireless communication interfaces to control ventilation systems is proposed. With this approach will be possible to maximize the benefits optimizing the relationship between energy consumption and worker's performance, reaching at the same time the best health and safety conditions (Babu et al., 2015).

2 CONCEPTUAL PROBLEM

The problem to be analyzed and addressed is the assessment and control of the interaction between the workplaces' environment in underground mining activities and the exposed workers.

It's well known that this environment - globally understood - can lead to several kinds of negative consequences for human beings and, in particular, affect their health conditions (Donoghue, 2005; Balbus & Malina, 2009; Kjellstrom & Haylee, 2009; Peters et al., 2016), the operating safety conditions (Eston, 2005; Sanmiquel, 2010; Kumar et al., 2016) and their productivity levels (Niemela *et al*, 2002; Kjellstrom *et al*, 2009; Ismail *et al*, 2010; Costa *et al*, 2011). These effects are the result of a set of adverse environmental conditions (Gancev, 2006; Vutukuri & Lama, 2010) which have different genesis, such as the existence of particles, fumes and dusts, in the air (physical agents), gases and vapors (chemical agents), microorganisms (biological agents) or extreme temperature and humidity conditions (thermal environment), among others.

Within the scope of this article, only the aspects related to the thermal environment will be addressed (elected as the central problem), considering that the other types of contaminants in presence have concentrations below the allowable limits, so do not significantly affect the workers. If the contaminants levels are not reduced by the pre-calculated ventilation conditions, the global ventilation systems should be re-calculated in order to reduce the concentration of the most critical contaminant to allowable values. As an additional note can be pointed that in mining activity is widely accepted that:

i) the environmental conditions inside the mine are controlled by regulating two ventilation systems (the main ventilation system is responsible by the overall air flow introduced into the mine; the secondary (or auxiliary) ventilation system provides localized air delivery to critical points as the working fronts);

ii) improving the environmental conditions in underground mining is accomplished by increasing clean air flow, in order to restore oxygen levels and promote contaminants dilution (Gancev, 2006).

In a hot environment, the operation mode for improving thermal environment conditions (decreasing in temperature by increasing air flow rate) has a positive effect on reducing physical and chemical pollutants. This allows focus the proposed approach to the problem only on the thermal environment variables. However, of course, should not be neglected the monitorization of the other factors.

3 METHODOLOGICAL ASPECTS

As first step, the variables that will enable the assessment of the real conditions in which underground mining activities are developed, are measured. The parameters to be monitored comprise three levels: metabolic rate, environmental conditions and electrical consumption, as shown in Figure 1.

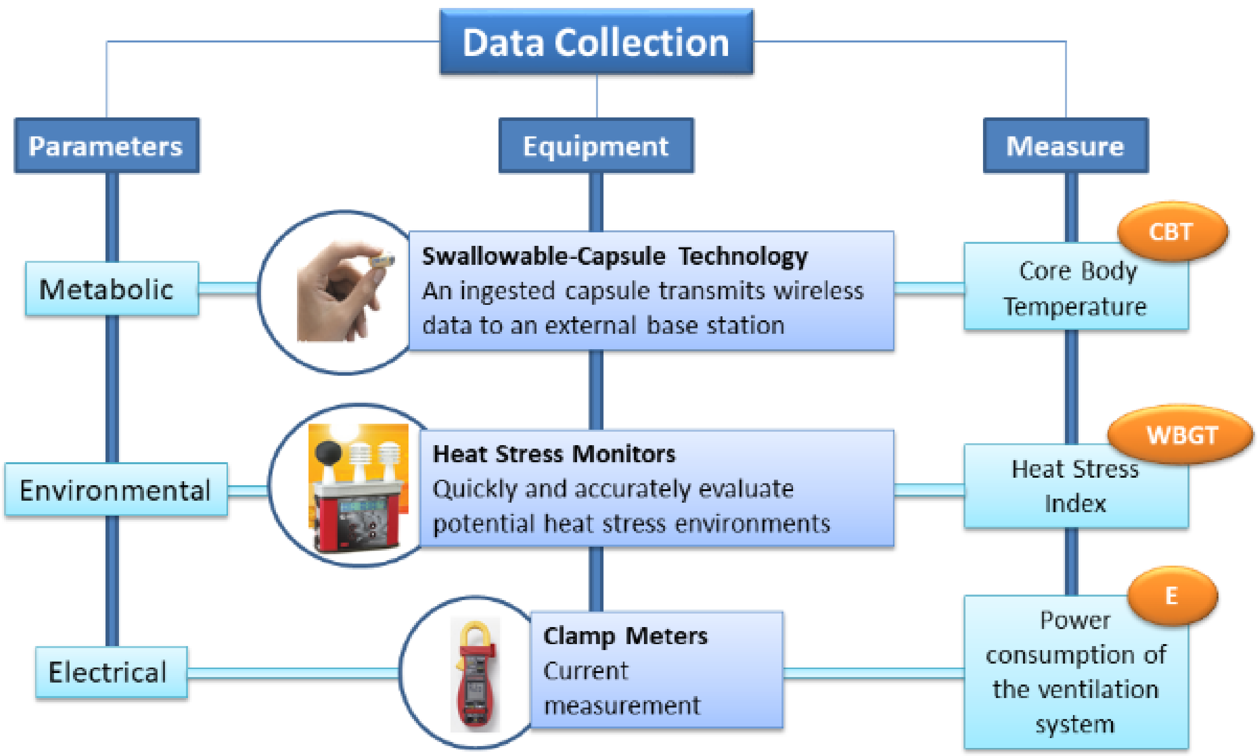

Figure 1 – Data Collection: Parameters, Equipments, Measures

Figure 1 shows the equipment and technologies (swallowable-capsule, heat monitor stress, clamp meters) (Mc Caffrey *et al*, 2008; Costa *et al*, 2012; S.A., 2017), used in the measurement of each variable values related with each of the parameters of interest: Core Body Temperature (CBT), Wet Bulb Globe Temperature Index (WBGT) (ISO 7243:1989) and Power Consumption (E). The values of these variables (CBT, WBGT, E) are the 'input signals' in the quantitative model to be used (detailed in section 4) in order to achieve the optimal operation point (inside the mine) (Sousa, 2014; Roghanchi and Kocsis, 2017).

In the second step, through the relationships established in the model, all variables are transformed into their corresponding economic values. This step is performed using cost optimization software (Lindo, 2017). As result, a solution is obtained minimizing costs, and ensuring the necessary physiological performance (Guedes & Baptista, 2011) and optimizing environmental conditions (ISO 7243: 1989) for the operation.

Thirdly and finally, the secondary ventilation system optimum level is achieved by using a communication interface between the respective control system and the optimization software. It is an iterative process designed to achieve the variable values stabilization at each desired level.

4 QUANTITATIVE MODEL

The development of the model to be used for the relationship between the variables (whose structure is shown in Figure 2) consists of two steps: a first one, A, in which are establish the functional relationships and the physical parameters; and a second one, B, where the variables and their corresponding amounts are translated into monetary values.

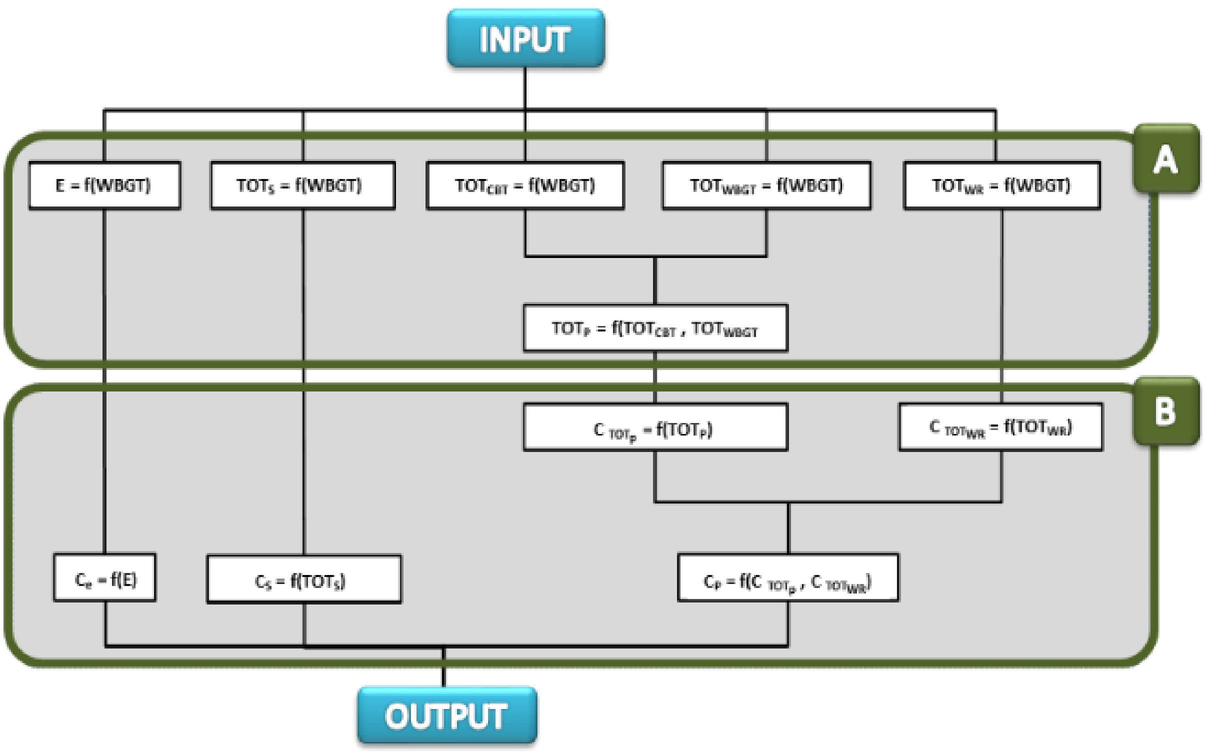

Figure 2 – Model structure. A - Functional relationships and physical parameters; B - Economic relationships and parameters

This conversion allows, on one hand, the necessary standardization and dimensional consistency, for subsequent application of the optimization method and, on the other hand, an easy perception and communication of the results' impact in a measurement unit of widespread interpretation (€ (euro), $ (dollar), £ (pound), etc.).

The design of the standard multifactorial model (figure 2) is based on a set of variables, concepts, relationships and consensual assumptions in the academic community, which are enunciate below.

The first aspect to be considered is to find a variable that could measure worker's performance decrease when being subjected to the severest conditions (e.g., activities in the workplaces with more critical thermal environments and tasks with higher metabolic rates). For that purpose was adopted the so-called 'Time Of Task' (TOT), proposed by Parson (2009). That measure enables to quantify - in time units - work breaks, associated with safety problems (TOTs) or due to be reached the maximum values defined for Core Body Temperature (CBT) (Guedes & Baptista, 2011) or for the thermal stress index (WBGT) (ISO 7243: 1989) or, also, measuring the reduction in work rate (WR), which arises as a form of human adaptation to adverse thermal environments (hot and humid) (Kjellstrom *et al*, 2009; Miller *et al*, 2011). In any case, the TOT values (*s*, *p* or *wr* index) represent a loss of production time caused by extreme heat environment conditions (high temperatures and humidity levels).

A second point considered in the model design is the relationship between the thermal environment conditions (WBGT) and the Time of Task (TOT) (group A, figure 2). It is widely recognized that the health, safety and productivity of workers are adversely affected by the deterioration of the thermal environment conditions at the workplace and *vice versa* (Donoghue, 2005; Ural & Demirkol, 2008; Zhao *et al*, 2009; Wyon, 2010; Rodrigues *et al*, 2011). Accordingly, functions were established using the WBGT index as independent variable in the quantification process of the remaining variables (dependents). This option enables the estimation of the 'TOT' times as a function of WBGT index (through the initial calibration and parameterization of model equations, for each real situation). The same strategy was applied to define the relationship between the fans power consumption (E) and the WBGT index. In this case, as referred before, it is assumed that inside the mine the environmental conditions control can only be done through the installed ventilation system (Webber-Youngman, 2005; Taylor, 2006; Toraño *et al*, 2011), so there is an inverse relationship between the energy consumption of such equipment and the WBGT index, i.e. to lower WBGT index values is necessary to increase energy consumption (and *vice versa*).

A third set of functions - which constitute the B group of figure 2 - convert unproductive times (TOT) in their respective economic impacts, according to the cost structure and revenues of the companies.

Finally, it should be noted that the application of this model - whose detailed presentation can be found at Sousa (2014) and Sousa & Baptista (2014) – allows to achieve optimal cost-effective solution (output), using the values of the WBGT index and electric energy consumption (E) as inputs, for every moments and situations.

It is emphasized that in the following part of this article will be considered a variant of the above described model, in which worker's CBT value is measured in real time, through an ingestible temperature sensor and its signal is sent online via WiFi to the main system. The availability of such data replaces CBT determination as a WBGT function, which will reduce any 'noise' introduced in the model and provide more accurate results.

5 INTEGRATED SOLUTION

In this section is described the integrated approach that aims to obtain feasible optimal solutions. These solutions can be implemented automatically and in real time, by using new data acquisition technologies, information processing software and wireless communications. In figure 3 is shown a schematic diagram of the model, with the respective modules and interfaces (Moridi et al., 2018).

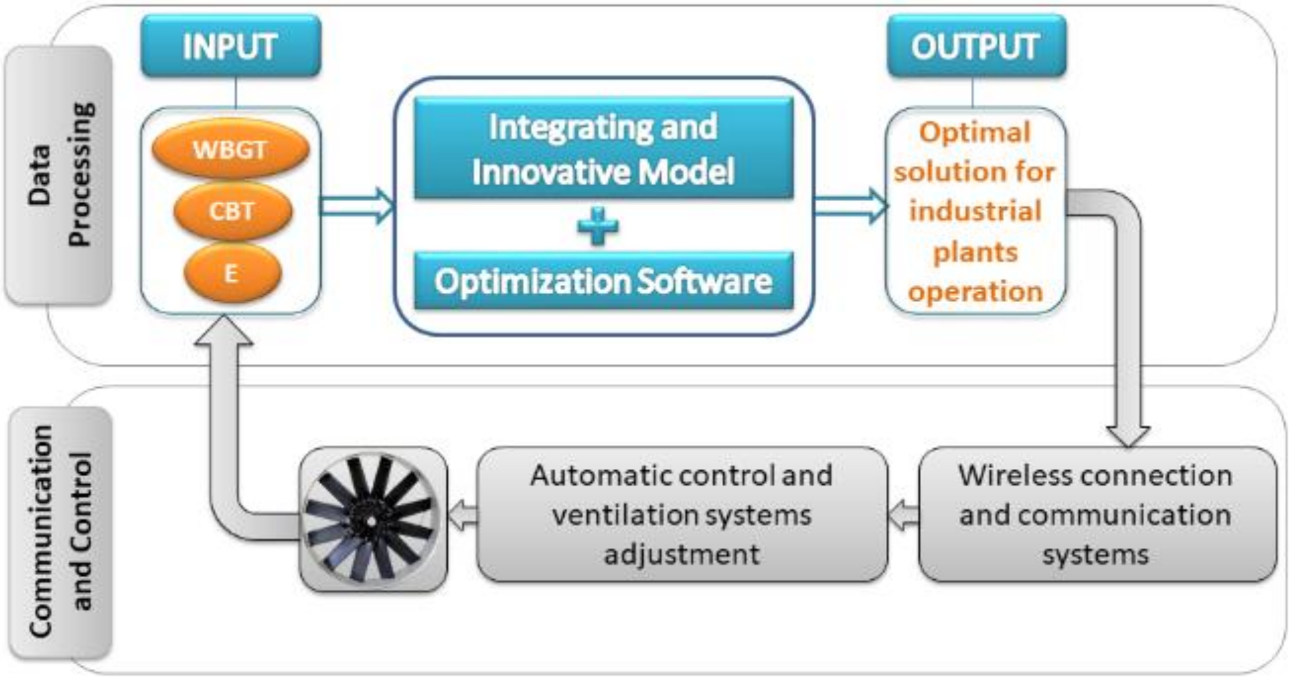

Figure 3 – Integrated Solution

As can be seen in Figure 3, there are two separate and interconnected modules that are designated respectively by "Data Processing" and "Communication and Control". The first one contains the whole set of instruments and tools already described, namely, the input variables (WBGT, CBT, E), the model within the functional relationships between variables and the optimal solution (output). In this module is also referred the optimization software (Lindo, 2017), as an essential complement to the process, which operates over the model and leads to the final solution.

In the second module, reference is made to the wireless communication interface between the software and the ventilation system command controllers that enable its adjustment to the desired conditions. It is noteworthy that the interest of the application of such technologies in the context of the underground mining activity is considered vital in a perspective of management and occupational safety (Walker, 2010; 2012).

It should be noted that the interconnection of the two modules enables automatic self-regulation of electromechanical ventilation systems installed. This process is based on iterative cycles until the optimum operating point and the system stabilization will be achieved.

It should also be noted that the solution to be implemented (output of the 'Data Processing' module) is the input of the ventilation system command module ("Communication and Control). In turn, the output of this second module affects the input variables values of the first module (WBGT, CBT, E). The process is repeated until converge to the desired optimal solution.

6 CONCLUSIONS

The proposed solution merges the resolution of the cost optimization problem with adequate conditions of safety and health and also with productivity. Also converges to a maximum level of performance, on considering and balance the effects of the different factors involved such as environmental, metabolic and physical. It is a practical and versatile application proposal, which adaptation to each situation is done by the initial calibration of the model parameters. The fact that the model's output be expressed in monetary units allows highlighting the economic impact of the solution and a better results perception by all the stakeholders.

The use of new technologies and tools for data acquisition and processing (as well as platforms, communication and wireless control interfaces) enable measurements, responses and actions in real time. The online and permanent monitoring of the variables (e.g. CBT) allows working closer to the operational and metabolic limits, which improves productivity and, consequently, the economic income of the companies. This is a crucial aspect that reflects the interest and usefulness of these new technologies combined with the relational model and the optimization software, in order to assertively answer the problems and faced challenges.

As final note, it is noteworthy that the model structure allows its application to other activity sectors (e.g. greenhouses, bakers, smelting) - beyond the underground mining industry – by defining the initial set of parameters that represent each case. For this purpose, it is only necessary that there are similar conditions of thermal environment (extreme conditions of temperature and humidity), which makes its potential use more diverse and comprehensive.

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