Mapping For Literature, Conceptual And Theoretical Framework And Methodology: Case Of Hot Deep Mining Ventilation Engineering Evaluation And Design

Peter M. Lukonde, Peter R. K. Chileshe

Abstract: The paper reports the layout of a mapping process for literature, theoretical and conceptual framework and methodology for mining ventilation engineering evaluation, design and methodology for a hot deep mine. The purpose of mine ventilation is to provide suitable environmental conditions in working places that promote comfort and efficiency as well as the safety and health of underground personnel. The objectives addressed in this paper include: (a) evaluation of a current mine ventilation system for a hot deep-level mine, taking into account the existing ventilation system infrastructure, for building of a mine ventilation baseline parametric database for subsequent end of life mine ventilation design; and (b) design of the extension end of mine life ventilation system taking into account increased production, high geothermic gradient and subsequent increase in depth of mining. The methodology used in evaluating an existing underground mine ventilation system and designing the extension end of mine life ventilation system employed three stages: (i) Literature mapping to identify authors, titles and technical papers at global, regional, and national/district scales relevant to the research; (ii) Conceptual and theoretical framework mapping to extract a kernel or core of concepts, hypotheses and theories from the literature map to drive the formation of methods of implementation; and (iii) Methodology and implementation mapping to direct and control the processes of data collection, analysis and interpretation. A sample case study of a deep-level underground mine has been used in this paper to provide examples of data collection, data analysis and interpretation, key findings and results, discussion and ‘what is new’, conclusions and recommendations, when the proposed mapping process is employed.

Index Terms: conceptual and theoretical framework mapping, Literature mapping, methodology and implementation mapping, mine ventilation, mine ventilation engineering, ventilation design

1 INTRODUCTION

Mapping is a strategy of directing or analysing or identifying scenarios, events or situations in a way that generates a way forward, or establishes the groundwork for something whether defined or not. In the context of this paper, the mapping process undertaken for a sample case study was to develop a sequence for a route of research from the point of conceptualization of a mine ventilation engineering problem and onward. The paper demonstrates setting of objectives which translates into literature mapping, conceptual and theoretical mapping as well as methodology and implementation mapping. These maps are then used to derive a qualitative and quantitative database which can be used to facilitate data collection, analysis and interpretation to the point of discussion of key findings and results. The findings are then reviewed and benchmarked to existing literature in a process called ‘What is New?’ and, thereafter generation of conclusions and recommendations for the research project. For the purpose of this paper, examples from a sample case study were used for explanatory purposes.

2 OBJECTIVES

The main objectives of the study were:

a) To evaluate an existing mine ventilation system for a hot deep mine in order to derive a parametric database for designing a ventilation system of future mine extension.

b) To design an extension of end of mine life ventilation system, taking into account increased production, high geothermic gradient and increased depth of mining.

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3 LITERATURE MAPPING
A map is a schematic or scaled representation of terrestrial or celestial terrain or space. A literature map is a schematic representation of the literature on a specific topic [1], which identifies authors, titles and technical papers at global, regional, and national/district levels relevant to the research, an example of which is shown in Figure 1. The literature map shown in Figure 1 is a small part, for convenience here, of all the literature actually covered. From the literature mapping,
relevant fundamental concepts, hypotheses and theories, applicable to a hot deep mine, are identified as shown in sections 3.1 to 3.10.

3.1 Airflow Fundamentals
The flow of air along an airway is always from a point of higher pressure to a point of lower pressure. Velocity heads and velocity head differences are so small that only static pressure may be utilised in the calculation of pressure heads for downcast shaft systems. When no major changes in cross sectional areas (shafts, fan drifts) are anticipated in a mine, velocity pressure will be excluded when analyzing airflow in the primary downcast shafts [2]. In calculating the pressure head for the upcast shaft system, however, both velocity head and static pressure are used. The pressure head then is equal to velocity pressure plus static pressure [3].

3.2 Airflow Resistance
The resistance encountered in airflow in mine ventilation airways result from two sources: (i) friction and (ii) shock [4].

In general, actual frictional losses account for 70% of air pressure losses; other sources such as viscosity are ignored since airflow in mine openings is virtually always turbulent. Shock and frictional pressure losses for all general consideration account for about 30% of all pressure losses. The Atkinson formula is employed in estimating the total losses in mine airways including upcast shafts as it is widely used by researchers. Shock losses often occur when airflow changes direction (for example at bends), when openings expand or reduce in cross section (for example at obstructions and regulators) or when the changes involve both cases (for example at junctions and splits). In this study both frictional and shock pressure losses for various airways along the tunnels (drives, crosscuts and raises) are assumed to be overcome by auxiliary fans positioned in various intake airways in the mine [5]. The airflow quantities and velocities along airways are assumed to be sufficient to overcome frictional and shock losses.

3.3 Air Leakage Patterns
Leakage phenomenon is often complex and the quantity of air leakage that occurs is a function of the difference in pressure in front of or behind the control devices, the construction and the condition of the devices, and the area exposed [6]. The leakages of air quantity measured at the fans can at times range from 40-50% of the measured quantity, which is substantial. Generally, severe air leakages are experienced through old stoppings [7]. Ramani [8] carried out studies to determine leakage across stoppings under several airflow conditions and graphical evidence indicates that the rate of air loss is variable over the longitudinal span of the airway, the largest values being furthest from the point of the working face, the loss of up to 75% occurring in the first half of the airway [9]. Air leakage underground is often underplayed, because of the difficult in measuring it. Where volume measurements can be done on each side of the leakage source, these measurements are not only more reliable than visual inspection, but may also be used as a basis for estimating leakages. Air leakage apart from not improving safety and health conditions, increases the cost of ventilation in terms of the volume of air required into the main split [10]. Air leakage should therefore, be kept to a practical minimum. In the sample case study used in this paper air leakage has been considered to determine its impact on the quantity flow of air both in the primary and secondary ventilation circuits. By comparing the total volume of air measured on surface upcast fans with that measured at the collection return points of the upcast shafts underground, the amount of air leakage can be estimated [11].

3.4 Airflow Circuits
Airflow distribution generally follows two basic circuits or a combination of airways namely; series or parallel or parallel with series. Pressures are different at each point. In series flow combinations, the airways are connected end to end with the same quantity flowing through each of the airways. In parallel flow, all airways start at the same point and end at the same point. Pressure difference between the ends of each airway is the same [12]. In parallel flow, air quantities can be split (air splitting) and distributed as “natural splitting” or “controlled splitting”. In natural splitting, the highest quantity flows in the least resistance split and vice versa. In controlled splitting, the quantity of air required in each airway is specified, and naturally, this is not possible in natural splitting [13]. Cross ventilation is typically in crosscuts between parallel drives [39].

3.5 Mine Heads
A mine head is constituted by three (3) distinct pressure heads, namely; Static Head (Hs), Velocity Head (Hv), and the Total Head (Ht). The static head is the sum of the friction and shock losses in the free split of the mine. The velocity head is the head due to the velocity of the air at the discharge of the mine (upcast shaft). The total head is the sum of the two pressure heads [14]. When the mine Head (static, total or both) is plotted against the quantity, the resulting curve on the graph is known as the “mine characteristic curve” [15]. Mine characteristic curves are useful to visualise the solutions to ventilation problems and to facilitate the selection of fans for mine ventilation systems. In the example study, the sum of velocity and static pressures make up the total pressure head for the upcast ventilation system UC 1 and UC 2 main upcast fans.

3.6 Mine Ventilation Networks
A mine ventilation network is a simple network in which the series and parallel airways may be combined through the equivalent resistance formulae into one airway with a resistance equal to the network resistance. Mine ventilation networks are however, complex in nature. Solutions for airflows and pressure head, for large ventilation networks, whether simple or complex can be obtained through the use of computer programs that apply the mathematical theory of networks and physical laws of mass and energy conservation to solve the head-quantity distribution problem [16]. In the example sample case study, a computer program that is available at some mines has been used to simulate the designed ventilation network for the area under study. The computer software in use at one mine is known as VENTSIM [17].

3.7 Review of Heat Load in Mine Ventilation Engineering
The review of heat load in mine ventilation engineering literature at global, regional, and national level involves a focused review on mine ventilation engineering for deep level
mining of technical papers, books, journals, previous research studies, and internet search as mapped, for example, in Figure 1. The review is undertaken in order to define the boundaries of existing knowledge on deep mining ventilation design in general, and with respect to a selected mine, as applicable in particular. The concept of heat load as it relates to deep-level mines and its impact on ventilation air had a special focus in order to understand air cooling in underground deep mines. Since heat is a major determinant in the estimation of air quantity (volume) and velocity in the airways, calculations involving the properties of air such as its wet-bulb temperature, density and humidity can only be successfully carried out if the above variables are accurately measured using the existing instruments [18]. The review was not intended to ‘re-invent a wheel’ in as far as empirical formulae for estimating parameters of air are concerned. The concept of this literature review was merely to identify and isolate empirical formulae and theoretical concepts of airflow as they relate to mine air cooling in deep-level mines [19].

3.8 Heat Consideration in Deep-level Mines
Table 1 shows estimates of the amount of heat picked up by ventilation air from the rock in a deep South African gold mine (Witwatersrand) with a rated production of 100,000 tons ore per month [20].

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Rate of production (Tonnes)</th>
<th>Heat pick up (kJ/s or kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>100,000</td>
<td>3,500</td>
</tr>
<tr>
<td>1,200</td>
<td>100,000</td>
<td>5,300</td>
</tr>
<tr>
<td>1,800</td>
<td>100,000</td>
<td>8,800</td>
</tr>
<tr>
<td>2,400</td>
<td>100,000</td>
<td>17,600</td>
</tr>
<tr>
<td>3,000</td>
<td>100,000</td>
<td>31,000</td>
</tr>
</tbody>
</table>

The fundamental laws of fluid flow in an airway do exist and are certain and solidly founded on credible scientific experiment [21]. However, what is not solidly fixed is the approach to ventilation design involving parametric data which often depends on the researcher’s personal experience coupled with the turbulent nature of air in mine airways [22]. The temperature of air, its quantity and quality in an underground airway can change at any given time during flow. The control of air in underground mine ventilation is a critical factor in providing comfort and safety to personnel working in various areas of the mine [23]. The maximum wet-bulb temperature allowed by law for provision of an environment that is conducive in any underground area varies from country to country. This is regulate by the Law of the land and is governed by scientifically established baselines for diluting air contaminants [24]. Since heat is one single contaminant that influences the ventilation design parameters of a deep-level underground mine, it will be given special consideration in this review (Taylor et al, 2005).

3.8.1. Heat review at global level
When planning to deepen an existing mine it is important to estimate or predict what the wet-and dry-bulb temperatures of air will be in the airways and working areas [25]. The heat generated due to the geothermal gradient of a mine should be quantified in order to determine the air volumes required to dilute it and also dilute other air pollutants such as dust and noxious gases in a mine [26].

3.8.2. Heat review at regional revel
The ventilation design parameters of a mine ventilation system are governed by the concepts and theories of two (2) fundamental Laws of Thermodynamics [27]. High temperatures in deep-level mines (common in South African gold mines) have an adverse effect on the comfort and efficiency of workers and to some extent on their safety and health [28].

3.8.3. Heat review at National Level
The wet-bulb temperature, for a given air velocity, can be kept below the critical (legal) limit provided sufficient volume of ventilation air is maintained in the working area. Deep-level underground mines in Zambia often experience high wet-bulb temperatures in working areas due to the geothermal gradient. The heat generated by the geothermal gradient of the mine has a bearing on the design of the ventilation system [29].

3.9 Fundamental Laws of Thermodynamics
The three (3) fundamental laws of thermodynamics can be applied in forming the theoretical framework of this study. The three laws of thermodynamics:

a) First Law: “Energy cannot be created or destroyed in an isolated system”.

b) Second Law: “The entropy of any isolated system always increases”.

c) Third Law: “The entropy of a system approaches a constant value as the temperature approaches zero”.

The first and second laws of thermodynamics constitute the most common mine ventilation equation, namely, Bernoulli’s equation [30]. The theory of energy flow as reflected in Bernoulli equation is based on the concept that the energy content of any flowing fluid or gas is made up of three quantities; enthalpy (thermal energy stored in the fluid and energy due to pressure of fluid), kinetic energy due to its velocity potential energy due to its mass and gravitational pull. Enthalpy is commonly referred to as total energy of a substance or fluid in motion. In the general analysis of airflow, Kirchhoff’s two Laws of turbulent fluid flow based on the modified Bernoulli’s Equation of heat flow have been applied. The two laws are hereby re-stated as follows:

a) First Law: “The algebraic sum of all mass flow rates at any junction is zero”, that is $\Sigma M = 0$ kg/s. Where mass flowrate $M = w_d Q$, and $w_d$ and $Q$ are the air density $kg/m^3$ and volume flow rate $m^3/s$ respectively.
b) Second Law: “The algebraic sum of all frictional pressure drops around any closed mesh, less any fan and natural ventilating pressure, is equal to zero”, that is; \( \Sigma \Delta p = 0 \) Pa. Where, \( \Delta p \) is the pressure drop in units of Pascal (Pa).

3.10 Key Findings from Literature Mapping
The key findings from the literature map are stated in sections 3.1 to 3.10, inclusive, from which some important points are extracted and itemised below:

a) Heat is measured in units of kilo Watt (kW) and is often assigned the term “Heat Load”, which is a measure of the amount of cooling needed to reduce its impact on the wet-bulb temperature (WBT) of air in an underground working environment.

b) The wet-bulb temperature (WBT) of air has greater influence on the cooling effect of air on the human body rather than the dry-bulb temperature (DBT).

c) Low wet-bulb temperature (WBT) is therefore an essential component of good ventilation in any operating underground mine.

d) The geothermal gradient (increase in virgin rock temperature) is directly proportional to increase in depth of mining and therefore, affects the wet-bulb temperature (WBT) of ventilation air in a deep mine.

e) High temperatures of air in deep-level mines in South Africa Gold mines are common and therefore use of refrigeration as a way of reducing the WBT of air is commonly employed.

f) Heat pick-up by air in some gold mines has recorded figures up to 31,000 kW in high production areas.

g) The common parameters used in the control of air ventilation include heat, WBT, air velocity, air volume (quantity), dust and obnoxious gas concentration.

h) Heat content, volume and velocity of air are critical parameters in designing a ventilation system in a deep-level mine.

i) Heat is a major contaminant that directly influences the WBT of air while the other contaminant such as dust and obnoxious gases affect the quality of air in the working environment.

j) The maximum allowable concentration (MAC) levels of dust and obnoxious gases are dictated by the legal thresholds set in accordance with scientific baselines for each country.

k) The quantity (volume) of air that can dilute heat and maintain the WBT of air below the legal/scientific threshold is also able to dilute dust and obnoxious gases in an operating underground environment.

l) Heat produced by diesel combustion from equipment, dust and obnoxious gasses are critical air contaminants in underground mines due to the confinement nature of working areas.

m) To maintain a comfortable working environment for high productivity requires that the WBT, the volume and velocity of air, and dust and obnoxious gas concentrations should be kept below the set legal/scientific thresholds for the mine.

There is little doubt that deep-level mines natural heat from exposed strata is a major cause of high temperatures. In regions of high virgin rock temperature (VRT), the increases in wet-and dry bulb temperature in horizontal airways may be attributed to almost entirely to the flow of heat from rock to air. But diesel equipment has in recent years emerged as a major source of heat in highly mechanised deep mines. Increased use of diesel equipment such as load haul dump units (LHD), front end loaders and dump trucks has added a new dimension of being a major contributor to the heat load in deep-level mechanised mines. Heat generated by diesel engine combustion flows to the air and thus increases the wet-bulb temperature of air in the mine workings [31].

4. CONCEPTUAL AND THEORETICAL FRAMEWORK MAPPING
Conceptual and theoretical framework mapping is divided into the generic (section 4.1) and specific (mine ventilation engineering evaluation and design) in section 4.2. In addition, a review is done which converts generalised fluid mechanics into the dynamics of airflow in mine tunnels and shafts (section 4.3). The summarised conceptual and theoretical framework map is discussed (section 4.4) and shown in Figure 2.
4.1 Generic Mapping

The conceptual and theoretical framework map of a study is a model that conveys generalised concepts and theories with the use of concepts, hypotheses, and theories coupled with mathematical symbols, boxes or/and arrows or other symbols. The conceptual framework is the researcher's idea or knowledge on how the research problem is tackled and is always anchored on the theoretical framework, which is a broader coverage of knowledge within the area of research study. The conceptual framework describes the relationship between specific variables or parameters that are identified in the theoretical analysis and are related to the problem. It therefore, narrows the various theories into concepts that lead to the formulation of empirical and theoretical formulae and mathematical equations. The conceptual framework thus explains the input data that is needed, the process of data and the output from the processed data of the entire study [32]. The theoretical framework of a study is the general outline of theories, hypotheses, ideas or models that relate to the problem that has been identified in a research study or thesis. The theories crystallize several factors that are important to the problem. A theoretical framework is therefore a road map that takes a researcher in an unfamiliar area of interest, seeking as much knowledge on the subject as possible, in order to siphon relevant theories that directly relate to the problem at hand. The theoretical framework is made up of scientifically tested theories that cover findings of many investigations on the subject under consideration. The conceptual and theoretical framework mapping, therefore, clarifies concepts and evolves relationships among the concepts, hypotheses and theories in a study. It provides a context for interpreting findings in the study and explains observations. The conceptual and theoretical framework identifies the starting point of research problems and postulates the procedure for arriving at the solution. It determines and defines the goal of the research problem and the specific areas to focus attention on during research. The conceptual and theoretical framework finally enhances the conceptual, hypothetical and theoretical foundation provided by the literature mapping. Figure 2 shows the process of evolution of concepts used in formulating empirical formulae for calculating the heat loads from various sources of the current and future mining areas. The design parametric data is obtained from the parametric data of the current mine ventilation system as derived from the three (3) Laws of thermodynamics. The literature mapping that can be used in practical application and methodology to generate a set of key findings and the way forward for the research and the ("square-law" of air in motion) end of life mine ventilation design and planning process.
4.1.1. Formulation of General Equations of Airflow
Kirchhoff’s two laws of turbulent flow as discussed under section 4.3 give rise to the basic formula for calculation of air quantity and pressure drop in a network circuit as follows:

\[ P = R Q^2 \]  

(1)

Where \( P \) is pressure loss (Pa), \( R \) is a resistance coefficient (N\(\cdot\)s\(^2\)/m\(^6\)) and \( Q \) is the volume airflow (m\(^3\)/s). The principle of Bernoulli’s equation is that air is a fluid of mass in motion (volume flow, \( V \) or quantity flow, \( Q \)) that induces air pressure drop in a ventilation circuit. The application of Bernoulli’s equation in Kirchhoff’s two laws of turbulent fluid flow is the basis for the empirical equation of airflow in a mine opening (tunnel)[33]. The quantity of airflow is then expressed either as volume flow, \( Q_v \) (in m\(^3\)/s), or as mass flow, \( M \) (in kg/s), as desired in the calculation. If the volume flow of air is measured and the cross sectional area of a mine opening (tunnel), \( A \) (in m\(^2\)), is determined, then the velocity of air at any point in the airway is calculated using the following formula:

\[ Q_v = v \cdot A \]  

(2)

where \( v \) is the velocity of air in m/s.

4.2 Specific Mapping for Mine Ventilation Engineering Evaluation and Design
The concept of mine air ventilation essentially involves the application of the theoretical concepts of fluid flow to the flow of air in mine openings. This concept includes the control of air movement, its amount, and its direction [34]. The principle involves the simultaneous control, within prescribed limits of the quality, quantity, and temperature-humidity of air. Air travels down mine openings (shafts or/and ramps) and through tunnels (haulages, drives or adits) to workings (faces) and for auxiliary purposes, through tubing or ducting [35]. The ultimate objective of air ventilation in the mine is to ensure suitable environmental conditions in working places at economic cost [36]. The concept of mine ventilation is to control dust, heat, and suffocating and toxic gases emitted underground, and the efficient distribution of the available ventilating air, so as to support production in a mine [37]. The concept of mine air ventilation essentially involves the application of the conceptual and theoretical framework mapping, as discussed in the foregoing sections, of fluid flow to the flow of air in mine openings. This includes the control of air movement, its amount, and its direction [38]. The principle of mine air flow therefore, involves the simultaneous control, within prescribed limits of the quality, quantity, and temperature-humidity of air. Air travels down mine openings (shafts or/and ramps) and through tunnels (haulages, drives or adits) to workings (faces) and for auxiliary purposes, through tubing or ducting [40]. The ultimate objective of air ventilation in the mine is to ensure suitable environmental conditions in working places at economic cost [41]. In this the concept of mine ventilation is to control dust, heat, and suffocating and toxic gases emitted underground, and the efficient distribution of the available ventilating air, so as to support production in a mine [42]. In the case at hand, it was theorised that the way forward was to evaluate the existing mine ventilation system and network at the mine, and then to use the derived parametric mine airflow, resistance and heat data to design and plan the deeper end of life of mine below. The evolutions of key factors, concepts, and variables used in this research which are based on two fundamental laws of heat and airflow, have been shown in Figure 2.

4.3 Appropriateness and Applicability of General Fluid Mechanics to Mine Airflow
The concept of airflow in an airway is essentially achieved by applying the laws of fluid flow to the dynamics of airflow in mine openings and workings (faces) [43]. The laws of thermodynamics are identified in the literature map (Figure 1), and are carried over into the conceptual and theoretical map (Figure 2). These laws, highlighted in Figure 2, for emphasis, are the foundation upon which mining ventilation engineering evaluation and design are based. Essentially, if you can control the air movement, its amount, and its direction, you can provide sufficient air to a working face for the comfort and safety of workers. But to provide ventilation air within the scientifically or legally prescribed limits requires quality control, it is vital to control both the quantity and temperature-humidity of the air at the same time. Air is coured through the mine openings (shafts or/and tunnels) and workings (faces) and for auxiliary purposes, through tubing or ducting [44]. The above concept is appropriate since the ultimate objective of air ventilation in a mine is to ensure suitable environmental conditions in working places at an economic cost. Furthermore, it involves the control of dust, heat, and suffocating and toxic gases emitted underground and the efficient distribution of the available ventilating air, so as to support production in a mine [45]. Modern concepts of airflow still rely on the principles of fluid dynamics and the theory of turbulent flow. This concept is premised on the basis that ventilation airflow through underground openings (tunnels, drives, crosscuts, raises, ramps) is more often than not turbulent in nature. In the general analysis of airflow, Kirchhoff’s two Laws of turbulent fluid flow and modified Bernoulli’s Equation of heat flow has been applied [46]. Kirchhoff’s two laws are hereby re-stated as follows:

(a) First Law: “The algebraic sum of all mass flow rates at any junction is zero”, that is \( F M = 0 \) kg/s Where mass flowrate \( M = w a Q \), and \( w a \) and \( Q \) are the air density, kg/m\(^3\) and volume flow rate m\(^3\)/s respectively.

(b) Second Law: “The algebraic sum of all frictional pressure drops around any closed mesh, less any fan and natural ventilating pressure, is equal to zero”, that is; \( p = 0 \) Pa Where \( p \) is the pressure drop in Pascal (Pa).

4.4 The Way Forward to Methodology and Implementation Mapping
Based on the foregoing concepts, hypotheses and theories, the conceptual and theoretical framework mapping can be used in practical methodology and implementation (section 5). This would be to generate a set of key findings and the way forward for the research and the end of life mine ventilation design and planning process.

4 METHODOLOGY AND IMPLEMENTATION MAPPING
From the conceptual and theoretical framework map in the previous section, it is possible to identify the research activities and sequence necessary to construct the methodology and implementation map. The methodology and implementation map comprises three main mapping stages leading to
derivation of findings for ‘what is new review’, conclusions and recommendations, viz:

a) Stage 1 - literature mapping (Figure 1);

b) Stage 2 – conceptual and theoretical framework mapping (Figure 2); and

c) Stage 3 - methodology and implementation mapping (Figure 3).

Figure 3 shows the methodology and implementation mapping process used in obtaining primary and secondary data. The primary and secondary data was obtained through surface and underground inspections, measurements using various instruments, recorded, coded and tabulated for analysis and interpretation. The Computer software (Ventsim 3.5.0.8) was then used in a simulation exercise in order to confirm the results that were obtained from the empirical calculations. The confirmed data was then used in the design of end of mine life ventilation for the hot mine extension [48]. The collection of primary and secondary data should be done in Stage 3 as shown in Figure 3. The data collection would be undertaken through surface and underground surveys and physical inspection of primary and secondary ventilation infrastructure such as main upcast fans and shafts, downcast shafts, main intake and return airways and raises. An evaluation of the current production area would be conducted using comprehensive surveys, namely:

a) Air quantity survey;
b) Temperature survey;
c) Pressure survey; and
d) Dust and polluting gases survey.

The methods and techniques used in measuring included:

a) Smoke tube for airflow measurements;
b) Anemometer for measuring low and medium velocity;
c) Pitot tube for measuring pressure variations and high velocity airflow;
d) Konimeter for taking dust concentration samples;
e) Hygrometer for measuring wet- bulb and dry-bulb temperatures;
f) Water flow meters for measuring water flow rate; 
g) Altimeter for measuring pressure differentials;
h) U-tube manometer or barometer for measuring absolute pressures; and
Heat generated by broken rock (ore & waste)

\[ Q_{br} = M_{br} \times (VRT - DB) \times C_{pbbr} \]  

Where \( Q_{br} \) = Heat from broken rock kW
\( M_{br} \) = Mass of rock broken per month (waste and ore) kg
\( DB \) = Intake Dry Bulb Temperature °C
VRT = Virgin Rock Temperature °C
\( C_{pbbr} \) = Specific heat capacity of broken rock = 0.925kJ/kg °C

6 DATA ANALYSIS AND INTERPRETATION – AN EXAMPLE FROM A SAMPLE CASE STUDY

From the data derived from the methodology and implementation map, it is possible to calculate heat loads of various contributors to the mine air in the existing ventilation network as shown below in equations.

6.1 Data Analysis of Heat Loads from Various Sources of the Existing Mine

To determine the total heat load of the mine in current and future mining areas, scientifically calculations were made to determine heat from autocompression, broken rock, rock (strata) surfaces, diesel equipment, blasting of explosives, metabolic (human breathing), electrical fans, and fissure (thermal) water, a total of eight sources established empirical formulae were used in calculating the heat quantities [49]. Calculations were made to determine heat from autocompression, broken rock, rock (strata) surfaces, diesel equipment, blasting of explosives, metabolic (human breathing), electrical fans, and fissure (thermal) water, a total of eight sources.

Heat load generated by autocompression

\[ \Delta H = M_a \times C_{pa} \times \Delta t = C_{pa} \times \Delta t \times \Delta H \]  

Where \( \Delta H \) = Enthalpy due to change in Dry-bulb temperature of air
\( C_{pa} \) = Thermal capacity of air (= 1.005 kJ/kg °C)
\( g \) = Acceleration due to gravity (g = 9.81 m/s²)
\( \Delta t \) = Change in air temperature °C
\( M_a \) = Mass of 1 kg of air

Heat Load generated by exposed strata (rock surface)

\[ Q_s = 0.006 x k_s \times (L + 4 x DFA) \times (VRT - DB) \]  

Where \( Q_s \) = Heat from exposed strata (wall-rock) kW
\( k_s \) = Thermal conductivity of the rock W/m °C
L = Distance advanced by the face in a month, m (100.0 m)
DFA = Daily Face Advance (m) = 4.0 m
VRT = Virgin Rock Temperature °C
DB = Dry Bulb temperature of air (°C )

Heat generated by broken rock (ore & waste)

\[ Q_{br} = M_{br} \times (VRT - DB) \times C_{pbbr} \]  

Where \( Q_{br} \) = Heat from broken rock kW
\( M_{br} \) = Mass of rock broken per month (waste and ore) kg
DB = Intake Dry Bulb Temperature °C
VRT = Virgin Rock Temperature °C
\( C_{pbbr} \) = Specific heat capacity of broken rock = 0.925kJ/kg °C

Heat load generated by diesel-propelled equipment

\[ Q_{diesel} = Average monthly fuel consumption \times \delta_{d} \times C_{fuel} \]  

Where, Average monthly consumption of fuel is in m³/month
Fuel Density = \( \rho_d \) = 845 kg/m³
\( C_{fuel} \) = Calorific Value of diesel, is in MJ/kg

Heat Load generated by blasting of Explosives

\[ Q_{exp} = M_{exp} \times Energy released by ANFO/EMULSION \]  

Where Energy release for ANFO/EMULSION = 2,820 kJ/kg
\( M_{exp} \) = Mass of explosives consumed, in kg
ANFO/EMULSION = Ammonium Fuel Oil explosives

Heat load generated by Electrical Equipment (Underground fans)

\[ Q_{elec} = Fan Motor Power Rating \times LF \times (Motor Efficiency) \]  

Where Load Factor = 0.75 and Fan Motor Efficiency = 0.80 and Power Rating is in kW

Heat load generated by human respiration (Metabolic Heat)

Typical figures for the rates of heat produced by each person in a shift are given as follows;

At rest = 90 – 115 W
Light work = 200 W
Moderate work = 275 W
Hard work = 470 W

\[ Q_{met} = No.ofpeople during peak time x heat per person \]  

Where \( Q_{met} \) = Heat produced by human respiration, kW

Heat load generated by fissure (thermal) and service water

\[ Q_w = M_w \times C_{pw} \times (VRT - DB) \]  

Where \( Q_w \) = Heat from fissure water kW
\( C_{pw} \) = Thermal capacity of water kJ/C
\( M_w \) = Mass flow of water, l/s
DB = Intake Dry Bulb Temperature °C

The heat loads for various sources of the existing mine (Level 1 – Level 8) were computed by extrapolating the values for each source using the Air Tonnage Ratio of 1.40 to obtain the projected heat loads in the future (extension) mining area. (Level 8 – Level 13 ore zone). The projected heat loads for the existing mine are shown in Figure 4. Figure 5 shows the projected heat loads from various sources in the future mining areas (Level 8 – Level 13).
6.2 Interpretation of Heat Load Data from the Existing Mine

The parametric data on heat loads calculated for the existing mine were coded, tabulated and then converted into graphical data. Figures 4 and 5 show the heat loads from various sources in the existing and future mining areas, respectively, identifying the highest amount as being from diesel propelled equipment.
6.3 Verification of Spreadsheet Data Analysis from Computer Simulation Software (VENTSIM 3.5.0.8. Software)

The ventilation design parametric data obtained from the empirical calculation using excel computation was confirmed by a computer software (VENTSIM) simulation. The input data included main upcast fan air quantities for the two upcast fans (UC 1 and UC 2), airway resistance, sizes (cross sectional areas) and airway distances [50]. Three separate ventilation network runs were conducted, network errors corrected, and the final run yielded the following results shown in Table 2 for the existing and the end of life future extension of the mine.

![Graphical data of heat loads as calculated for various sources of the future mine (Level 8 – Level 13 ore zone)](image)

**Table 2: Comparative Data - Excel Spreadsheet (using Empirical Formulae) vs Computer Spreadsheet (using simulated results of Ventsim Software)**

<table>
<thead>
<tr>
<th>Type of Method used in calculation of Air Quantity</th>
<th>Air Quantity (m³/s)</th>
<th>Pressure shortfall (kPa)</th>
<th>Total Static Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Quantity (Volume) of air in the mine under the current ventilation system</td>
<td>925.0</td>
<td>0.00</td>
<td>11.9</td>
</tr>
<tr>
<td>2. Computer simulation (Ventsim)</td>
<td>923.4</td>
<td>1.08</td>
<td>12.98</td>
</tr>
<tr>
<td>3. Air Tonnage Ratio (ATR)</td>
<td>960.3</td>
<td>1.10</td>
<td>13.0</td>
</tr>
<tr>
<td>4. Psychometric Charts</td>
<td>943.6</td>
<td>1.10</td>
<td>13.0</td>
</tr>
</tbody>
</table>

It is important to note, however, that the software used in the simulation exercise was limited to the simulation of air quantity in the current and future mining areas and pressure drop in the three main upcast air return raises. It was not necessary to carry out a simulation of heat loads, as these were obtained using empirical formulae for the current mining area (Level 1 – Level 8 ore zone) and then extrapolating the calculated heat loads using the calculated ATR for the future mining area (Level 8 – Level 13 ore zone). The required volume of air for diluting the generated heat in the mine was determined using the calculated total heat load. The computer simulation of heat would only be necessary if the option of refrigeration of air was considered in the study. But this is not the case in this study.

6.3.1. Comparison of empirically calculated air requirement with computerised simulation output

Results of empirical analysis of air requirements using Air Tonnage Ratio and Psychrometry were then compared to the computer simulation results for the same ventilation network as shown in Table 3. The three results were a close match indicating that the empirical and computerised methodologies converged, indicating that the empirical mapping methodologies were valid and reliable, able to produce accurate results.
6.4 Designing the Future Ventilation Network Circuit
(Level 3 – Level 8 Ore Mining Zone)

The parametric data obtained from the evaluation of the current mining area (Level 1 – Level 8 ore zone) was used to draw the profile of the ventilation network for the current and future mining areas of the mine. This is shown in Figure 6. Figure 6 is a profile of the designed ventilation system for the future mining areas (Level 8 – Level 13 ore zone. The downcast service shaft is the primary intake airway of fresh air to all areas of the mine and is positioned in the centre of the mine. The two (2) main primary upcast shafts serviced by the main fans UC 1 and UC 2 draw out all foul air from the working areas as exhaust airways.

**Parametric Ventilation Design Data**

The parametric design data that was obtained from the evaluation of the current ventilation system and the computed values using excel spread sheet were confirmed by the computer software simulation were used as ventilation design parameters. The parameters assigned to the new service shaft, the current service shaft and the main shaft intake shaft (volume and velocity were also obtained from the computer software simulation.

<table>
<thead>
<tr>
<th>Type of opening</th>
<th>Size of opening</th>
<th>Current Figures</th>
<th>Current Figures</th>
<th>Volume (Design)</th>
<th>Velocity (Design)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Area- m²)</td>
<td>Volume (Q)</td>
<td>Velocity (v)</td>
<td>(Q)</td>
<td>(v)</td>
<td></td>
</tr>
<tr>
<td>Main Shaft (intake)</td>
<td>20.0 – 25.0</td>
<td>370.0</td>
<td>7.11</td>
<td>250.0</td>
<td>10.0</td>
<td>Shaft Collar</td>
</tr>
<tr>
<td>Main Shaft (service)</td>
<td>20.0 – 25.0</td>
<td>255.0</td>
<td>10.2</td>
<td>500.0</td>
<td>20.0</td>
<td>Shaft Collar</td>
</tr>
<tr>
<td>NEW SERVICE SHAFT</td>
<td>6.1m Diam.</td>
<td>0.00</td>
<td>10.0</td>
<td>174.0</td>
<td>10.0</td>
<td>Shaft Collar</td>
</tr>
<tr>
<td>Main Haulage</td>
<td>14.0 – 20.0</td>
<td>17.7</td>
<td>1.2</td>
<td>63.0</td>
<td>4.5</td>
<td>Underground</td>
</tr>
<tr>
<td>Drives (drill/acc.)</td>
<td>14.0 – 20.0</td>
<td>19.0</td>
<td>1.3</td>
<td>56.0</td>
<td>4.0</td>
<td>Underground</td>
</tr>
<tr>
<td>Main Ramp</td>
<td>14.0 – 20.0</td>
<td>22.0</td>
<td>1.3</td>
<td>56.0</td>
<td>4.0</td>
<td>Underground</td>
</tr>
<tr>
<td>Cross Cut (access)</td>
<td>14.0 – 20.0</td>
<td>17.3</td>
<td>1.2</td>
<td>56.0</td>
<td>4.0</td>
<td>Underground</td>
</tr>
<tr>
<td>Raise (intake)</td>
<td>4.0 – 6.0</td>
<td>7.2</td>
<td>0.8</td>
<td>8.80</td>
<td>2.0</td>
<td>Underground</td>
</tr>
<tr>
<td>Raise (return)</td>
<td>4.0 – 6.0</td>
<td>5.4</td>
<td>0.6</td>
<td>8.80</td>
<td>2.0</td>
<td>Underground</td>
</tr>
<tr>
<td>Diesel Workshop</td>
<td>14.0 – 20.0</td>
<td>17.7</td>
<td>1.2</td>
<td>28.0</td>
<td>2.0</td>
<td>Underground</td>
</tr>
<tr>
<td>Workshop (other)</td>
<td>14.0 – 20.0</td>
<td>14.7</td>
<td>1.0</td>
<td>28.0</td>
<td>2.0</td>
<td>Underground</td>
</tr>
<tr>
<td>Conv. Belt tunnel</td>
<td>7.0 – 9.0</td>
<td>13.5</td>
<td>1.5</td>
<td>17.5</td>
<td>2.5</td>
<td>Underground</td>
</tr>
<tr>
<td>Crusher Chamber</td>
<td>14.0 – 20.0</td>
<td>36.0</td>
<td>1.8</td>
<td>70.0</td>
<td>5.0</td>
<td>Underground</td>
</tr>
<tr>
<td>Draw Point X/C</td>
<td>14.0 – 20.0</td>
<td>15.2</td>
<td>1.1</td>
<td>17.5</td>
<td>2.5</td>
<td>Underground</td>
</tr>
<tr>
<td>Loading Box</td>
<td>14.0 – 20.0</td>
<td>12.0</td>
<td>1.0</td>
<td>14.0</td>
<td>2.0</td>
<td>Underground</td>
</tr>
<tr>
<td>Pump Chamber</td>
<td>14.0 – 20.0</td>
<td>8.5</td>
<td>1.3</td>
<td>17.5</td>
<td>2.5</td>
<td>Underground</td>
</tr>
</tbody>
</table>
6.6 Key Results from a Sample Case Study Example
The following were the key findings made from the example sample case study, using the present methodology and implementation mapping:

(a) The total quantity (volume) of downcast air that circulates in the current mining areas (Level 3 – Level 8) is 625 m$^3$/s.
(b) The quantity (volume) of downcast air that is required in the current and future mining areas is about 943 m$^3$/s (an increase of about 50%).
(c) The amount of air that flows in a number of current areas of the mine though sufficient to dilute dust and obnoxious gases, is not adequate to dilute heat generated in the mine in order to keep the Wet-bulb temperature of ventilation air below the scientific/legal baseline of 31°C.
(d) The geothermal gradient (increase in VRT due to depth of mining) of the mine has directly affected the wet-bulb temperature of mine air.
(e) The estimated total heat load generated by various sources in the current mining (Level 3 – Level 8 ore zone) is about 3,654 kW.
(f) Diesel equipment, geothermal gradient, and electrical equipment are the major sources of heat in the mine contributing about 1,792 kW (88% of the total heat load). This heat is significant to the ventilation system design.
(g) The total heat load expected in the future mining areas is 5,078 kW.

7 WHAT WAS NEW FROM THE SAMPLE CASE STUDY?

The literature mapping followed by the conceptual and theoretical framework mapping was used to construct the methodology and implementation map. The mapping process created a way forward consisting of newly conceived ideas from the study, as summarised in Figure 7, going beyond the previous boundary of knowledge which was based on the existing mine.

7.1 Findings
Findings made using the sample case study are listed below:

a) The total quantity (volume) of downcast air in the existing mine is 625 m$^3$/s at 11.9 kPa.
b) The total quantity (volume) of air required in the mine extension is 924.3 m$^3$/s at 13.0 kPa.
c) The shortfall in static pressure which is needed to boost the present ventilation system is 1.1 kPa, through the
introduction of two booster fans underground located on level 8.

d) If air leakage is managed properly and controlled below 20 % of the total air, it is possible to increase quantity (volume) of air in the working areas of the mine extension, which would ultimately lower the wet-bulb temperatures of air.

e) Air leakage should be controlled within the limits of 10-20% in order to minimise excessive air losses.

f) The heat load produced by diesel-propelled equipment can easily be calculated using diesel consumption for each equipment. For the sample case study, it was discovered that diesel-propelled equipment contributed the highest heat load (50 % of the total heat load), therefore diesel equipment has to be phased out or limited in the deeper mine extension.

g) The Air Tonnage Ratio (ATR) for the existing mine was 1.4.

h) The calculated heat load can be used to calculate the total quantity (volume) of air required in a mine extension ventilation system.

i) The ventilation system of an existing mine can be used in calculating the heat load of a mine extension. This is possible by employing empirical formulae which have been derived from the concepts of fluid flow that are enshrined in the three fundamental laws of thermodynamics.

From the foregoing, for the current sample case study, it is possible to maintain the wet-bulb temperature (WBT) of mine air below the scientific or legal threshold without use of refrigeration provided air leakage is kept below 20% of the total air and electric load, haul and dump equipment is used in place of diesel-propelled equipment in the production area of the mine.
8 CONCLUSIONS
For the sample case study, the following conclusions shown in italics were made from the findings:

Main objective 1
To evaluate an existing mine ventilation system for a hot deep mine in order to derive a parametric database for designing a ventilation system of future mine extension.

- The total quantity (volume) of downcast air in the existing mine is 625 m³/s at 11.9 kPa.

Main objective 2
To design an extension of end of mine life ventilation system, taking into account increased production, high geothermal gradient and increased depth of mining.

- The total quantity (volume) of air required in the mine extension is 924.3 m³/s at 13.0 kPa.

- The shortfall in static pressure which is needed to boost the present ventilation system is 1.1 kPa, through the introduction of two booster fans underground located on level 8.

9 RECOMMENDATIONS
For the sample case study, the following recommendations were made:

a) The new service shaft should be used as a downcast shaft in order to increase the amount of air in the current and future mining areas. This will increase the quantity (volume) of downcast fresh air from 625m³/s to 924.3m³/s.

b) Air leakage, both in the primary and secondary ventilation air circuits, should be reduced from the current level of 36% to 10-20%, by planned sealing of all practically accessible points of air leakage. This will increase the quantity (volume) of fresh air circulation in the current and future mining areas to 924.3 m³/s from the current 625 m³/s.

c) Diesel-operated load, haul and dump equipment should be replaced with electric units in order to reduce the amount of heat generated by diesel propelled equipment (the major heat contributor). This will result in a reduction of about 50% of the total heat generated in the mine with a corresponding reduction in wet-bulb temperature of mine ventilation air.

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REFERENCES


