Modular ventilation laboratory for educational purposes

http://dx.doi.org/10.1590/0370-44672023770066

Rita de Cassia Pedrosa Santos[1,4]
https://orcid.org/0000-0002-9296-3191
Michel Melo Oliveira[2,5]
https://orcid.org/0000-0002-4295-6479
José Margarida da Silva[1,6]
https://orcid.org/0000-0001-5695-7213
Claudio Lúcio Lopes Pinto[2,7]
https://orcid.org/0000-0001-9924-2824
Alan Kardek Rêgo Segundo[3,8]
https://orcid.org/0000-0002-9272-0667
Douglas Batista Mazzinghy[2,9]
https://orcid.org/0000-0003-2569-6932

[1]Universidade Federal de Ouro Preto – UFOP, Escola de Minas, Departamento de Engenharia de Minas, Ouro Preto – Minas Gerais - Brasil.

[2]Universidade Federal de Minas Gerais – UFMG, Escola de Engenharia, Departamento de Engenharia de Minas, Belo Horizonte – Minas Gerais - Brasil.

[3]Universidade Federal de Ouro Preto – UFOP, Escola de Minas, Engenharia de Controle e Automação, Ouro Preto – Minas Gerais - Brasil.

E-mails: [4]rita.pedrosa@ufop.edu.br, [5]michelmelo@demin.ufmg.br, [6]jms@ufop.edu.br, [7]cpinto@ufmg.br, [8]alankardek@ufop.edu.br, [9]dmazzinghy@demin.ufmg.br

Abstract

Improving a technical work environment encourages creativity and enhances research efforts. The conception of a modular ventilation laboratory aims at free construction and assembly of the air circuit in different shapes, sizes, and operational variations. The modules allow the development of academic experiences, automatic data acquisition from sensors, data analysis, and verification of concepts related to ventilation in underground mines. The modular ventilation laboratory uses a teaching methodology based on a playful and low-cost way to teach engineering, mainly underground mine ventilation. The aim of this work is essentially to propose the creation of a modular underground mine ventilation laboratory to facilitate engineering teaching and allow the simulation of real situations. The Plan-Do-Check-Act (PDCA) methodology was used to develop a framework for building the modular educational ventilation laboratory. This methodology encompasses project planning and studying, applying the Ventsim® software, and the design of a teaching laboratory with sensors and microcontrollers using the Internet of Things (IoT). The results involve the construction of a physical project with PVC (polyvinyl chloride) pipes and connections and electronic circuits. The project presents the main parameters monitored in underground mines and foresees the simulation of scenarios, aiming to facilitate an understanding of the concepts of fluid mechanics and mining ventilation. The conclusions indicate that using simulation in pedagogical practices develops several activities that contribute to innumerable learning and expands the network of constructive meanings as a learning strategy.

Keywords: underground ventilation, PDCA, Arduino, Internet of Things, sensors.

1. Introduction

The ventilation system ensures that pure air is taken into the mines, creating, and guaranteeing better working conditions, as well as preventing the entire structure from possible explosions and other consequences to the accumulation of dust and explosive gases. Adequate ventilation must ensure a breathable and safe atmosphere for underground mining work (McPherson, 1993; Alvarenga,2012; Dziurzyński *et al*., 2017). It is essential due to the natural hazards and technological processes that come the nature of mining (Costa & Silva, 2020; Szlązak & Korzec, 2022; Santos *et al*., 2022). Variations in the circulating air flow, resulting from pressure losses or decreases, are mainly related to two phenomena: friction losses and shock losses. Friction losses derive from the resistance to the passage of the flow that opposes the roughness of the walls, the cross section, and the perimeter of the excavations and/or ducts through which the air circulates. On the other hand, shock losses correspond to pressure drops resulting from the various changes in the geometry of a mine ventilation circuit that cause increased turbulence, whether related to the direction, section, or curves of the circuit (McPherson, 1993). Many scientists have used computational modeling (Dziurzyński *et al*., 2017), Computational Fluid Dynamics (CFD), and optimization algorithms to more efficiently simulate systems to design underground mine solutions (Xu *et al*., 2018; Neme *et al.,* 2011).

One of the most used and well-known programs for application in mine ventilation systems is Ventsim, used by mining companies, universities, consultants, government organizations and research. Software of Australian origin, suitable for carrying out analyzes of complete or sectored ventilation circuits (Ventsim, 2022). According to Costa (2017) Ventsim is a very important tool for making decisions regarding the improvement of the ventilation system. As an example of alternatives for analysis through simulations, there is the implementation or replacement of fans to supply the air demand on certain workface, or changes in the ventilation circuit with the advance or retreat of ducts. Simulation results, when satisfactory, can be safely put into practice, avoiding possible waste of time and materials when tested directly in the field. Ventsim is a complete integrated mine and tunnel ventilation software package for designing and testing ventilation circuits, including airflow, pressure, heat, gases, power, fire, and other types of ventilation information.

The ludic spirit contributes significantly to the development of the human being, of any age, assisting in learning, social, personal, and cultural development, facilitating the process of socialization, communication, expression, and construction of thoughts (Santos *et al*., 2021). According to Bould and Feletti (2017), learning is mainly related to understanding fundamental concepts and how to put them into practice. Playful activities can facilitate understanding of how ventilation circuits work in practice and how changes can affect the outcome. Ribeiro (2005) indicates that methodologies based on real or simulated problems boost the acquisition of knowledge and develop skills and attitudes in the professional scope of students. This modular mine ventilation laboratory allows students and researchers to make changes in the circuit modifying the airflow and studying the behavior of ventilation parameters, analyzing the differences in each chosen scenario (Santos *et al*., 2020).

The modular circuit developed in PVC enables studying the behavior of parameters related to ventilation and assembling different scenarios with pieces that fit together like a “LEGO” toy. Created in 1934 by the Danish and carpenter by profession, Ole Kirk Christiansen, the Leg Godt, known worldwide as LEGO®, means "play well", LEGO® has become a kind of universal toy. It is manufactured by the LEGO Group, whose original concept was based on a patented system of plastic parts that fit together, allowing countless combinations (LEGO®, 2021).

The construction of the laboratory contributes to academic knowledge, combining theories related to fluid mechanics and ventilation in underground mines using sensors to monitor temperature, pressure and air humidity. For the development and assembly of the laboratory, it was decided to use a tool for organizing and managing the process, the Plan-Do-Check-Act (PDCA) cycle. The PDCA cycle was proposed by Shewhart (2015) and disseminated by Deming (2000), for use as a problem-solving technique in the context of quality management (Ghosh *et al*., 2022; Peinaldo & Graeml, 2007; Campos, 2004). The literature on performance measurement contains several examples of researchers applying the PDCA cycle in various circumstances, such as manufacturing, education and employee development (Alam, 2014; Sangpikul, 2017). The PDCA cycle establishes the actions related to the planning and execution of a project, allowing increasing improvement in the process, since it is possible to reassess all stages of the process, thus making it possible to propose a new plan or improvements in the process (Seleme & Stadler, 2010). PDCA can be subdivided into four phases: Plan, Do, Check and Action (Varadejsatitwong *et al*., 2022). The Plan stage involves identifying a problem; the Do stage includes the execution of the Plan; the Check step involves data analysis; the Act stage consists of activities to fill the gaps and evaluate the results of these actions (Bhutta & Huq, 1999; Pham *et al*., 2012).

2. Materials and methods

The design of the modular laboratory aims to freely build ventilation circuits applied to the academic environment (Silva *et al*., 2021). The methodology allows many variations regarding the type of scenario, materials, shapes, sizes, available space, or even understanding of a real problem.

The construction project contemplates the reading of the parameters using microcontrollers that allow obtaining the values provided by the installed DHT11 and BMP280 sensors (temperature, pressure, and humidity of the air) along the circuit. The air velocity can be measured using hot wire anemometers positioned at desired locations.

The physical model construction used low cost and durable PVC pipe and joints with a diameter of 100 mm. This choice allows greater availability of parts with different roughness, different transversal option, and different materials along the circuit. The circuit swiftly re-configurates the induced static pressure changes and increases the testing possibilities in the laboratory. The modular PVC pipe segments are 50 cm and 80 cm long and can be fit together according to the desired scenario or available space for assembly. The constructive steps can be summarized as:

• circuit conception to study different parameters along its sections;

• circuit design in Ventsim® (VentSim, 2022) mine ventilation software;

• circuit analysis in the software and changes in the initial design;

• definition of the laboratory design;

• beginning of the construction of the circuit involving the choice of the type of material, length and diameter of the simulated sections;

• assembly of the circuit defining the necessary junctions;

• evaluation of available and necessary microcontrollers and sensors for installation;

• selection of technology to collect and to transmit data;

• definition of different scenarios to be studied.

The PDCA cycle is a classic management methodology, it is used continuously to improve processes, contributing to the alignment of operational and strategic stages. The proposal for using the methodology is in the management of project development processes (Figure 1). Planning (P) includes studies related to circuit design, defining the size of modules, installing sensors. Doing (D) includes running the tests and programming to read the data and test the sensors. Action (A) is a step that encompasses the needs for improvement, including adapting the process, creating laboratory practices, and listing the costs involved for each adaptation. According to the methodology concept, the PDCA is continuous, when the sequence is finished, it restarts afterwards, demonstrating that the cycle is always looking to improve its processes.

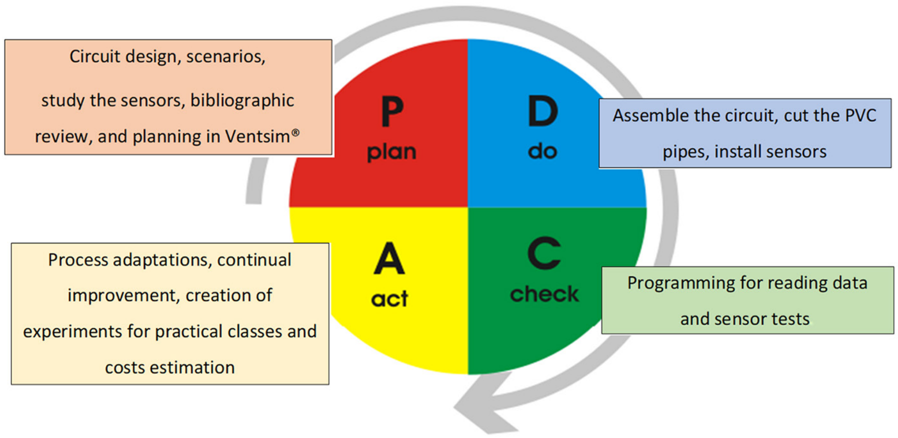

Figure 1 - PDCA Cycle (Adapted Seleme & Stadler, 2010).

3. Results

The results begin with the application of the first stage of the PDCA methodology. Planning the scenarios before starting the assembly is important to understand the system and to avoid unnecessary costs. The circuit design provides a possible representation of different scenarios that meet the theory previously checked. The study includes the size of the circuit, design configuration, location of the sensors and online recording of the variables chosen at different points, enabling the analysis of general pressure losses in the circuit.

Figure 2 represents a suggested circuit for the future creation of the modular laboratory using Ventsim® software - version 5.1 (Ventsim, 2022).

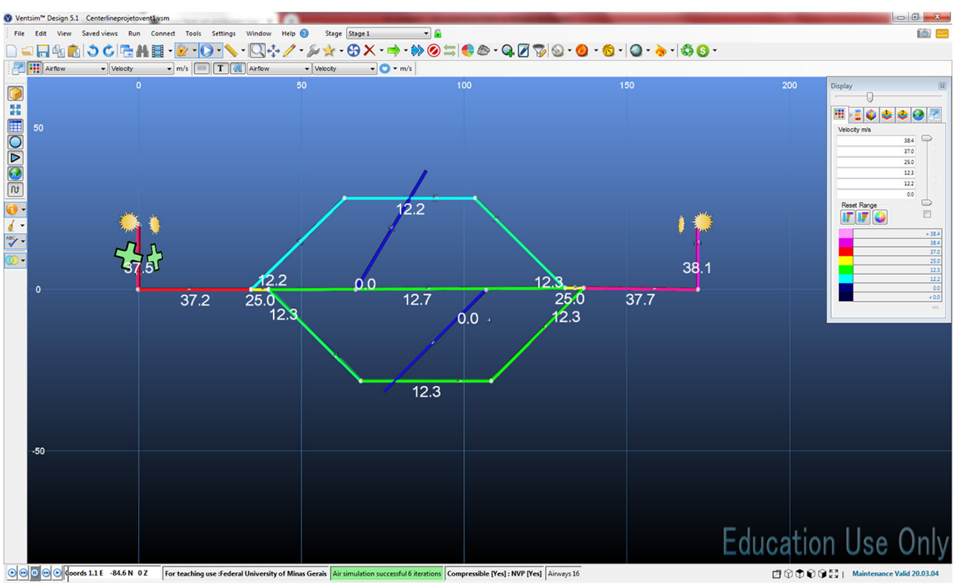

Figure 2 - Ventilation circuit (Ventsim, 2022).

Figure 3 represents a situation when the circuit branches are blocked, the air follows a straight path, in magenta, at the center of the design.

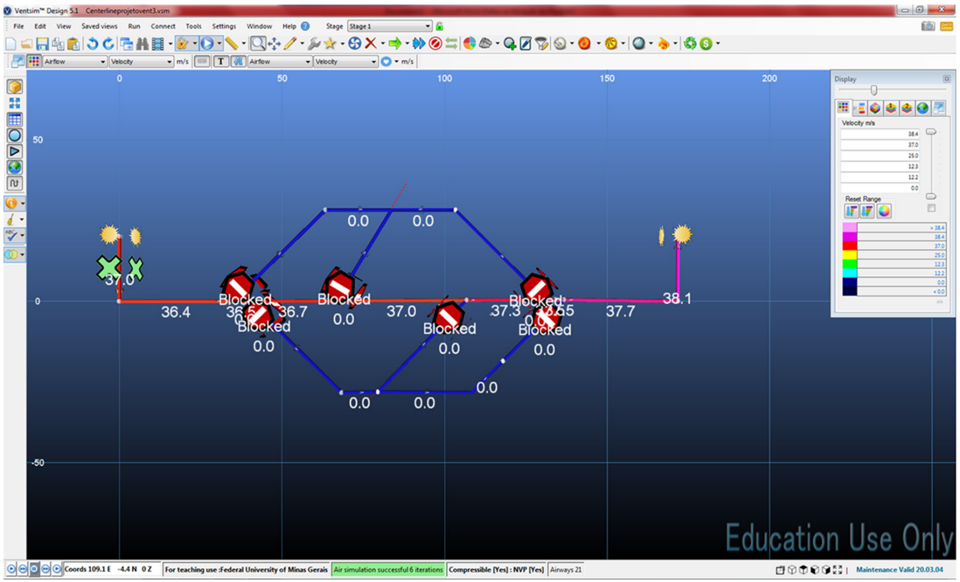

Figure 3 - Scenario blocking the crosspieces in the ventilation circuit (Ventsim, 2022).

Figure 4 presents the airflow redistributed through the other paths of the circuit. In these examples, Figures 3 to 5, only represents the airflow velocity.

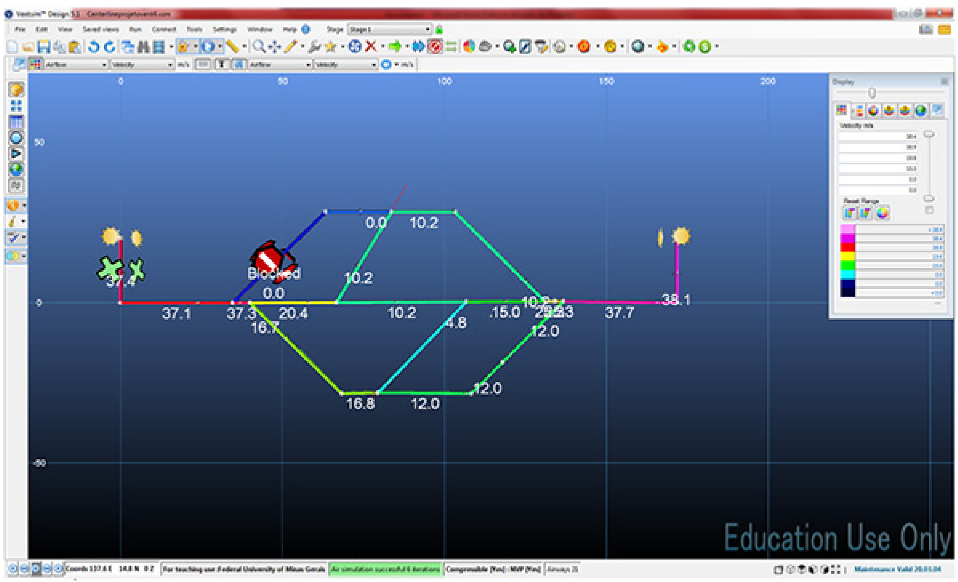

Figure 4 - The barrier in one of the lines of the ventilation circuit (Ventsim, 2022).

The projected barriers aimed to modify the airflow behavior and to study these interferences simulating an underground mine's real situation. This ventilation behavior is important for making operational and managerial decisions.

Following the PDCA cycle, the next step is the physical construction and instrumentation of the pipeline modeling for an underground mine using the PVC ducts and connections. The electronic circuit consists of an Arduino Mega board connected to sensors capable of reading ventilation parameter data at various points. The tests were performed with sensors installed in PVC tubes. A real time curve can be generated for the measurements of each sensor. The datasheet for each sensor presents the reference values and their accuracies. To define the sensors, the desired parameters, availability, and value of the sensors were considered.

The study encompasses studying the DHT11 and BMP280 sensors. The DHT11 sensor is a temperature and humidity sensor with an accuracy for humidity of ±5%RH, the measurement range is 20 to 95%RH. For temperature, the measurement range is from 0 to 50°C with an accuracy of ± 2%. The BMP280 sensor is the successor of the BMP180, with gains in terms of accuracy and energy consumption, being an absolute barometric pressure and temperature sensor. Accuracy is ±0.12hPa, which is equivalent to ±1m difference in altitude. Its measurement range is from 300 to 1100hPa and the temperature is from -40 to 85°C with an accuracy of ± 1°C. Both sensors work with 3.6V supply and the DHT11 also works with 5V. A series of 2-hour tests were carried out with the sensor reading frequency varying from 2 seconds to 1 minute. The sensors selected for this study were the BMP280, for monitoring barometric pressure and temperature, and the DHT11 sensor, to monitor humidity. It is worth noting that both have a temperature sensor, but the BMP280 sensor was used, due to its greater accuracy compared to the DTH11. A USB cable is used to connect the Arduino with a computer and for an external energy power source (Figure 5).

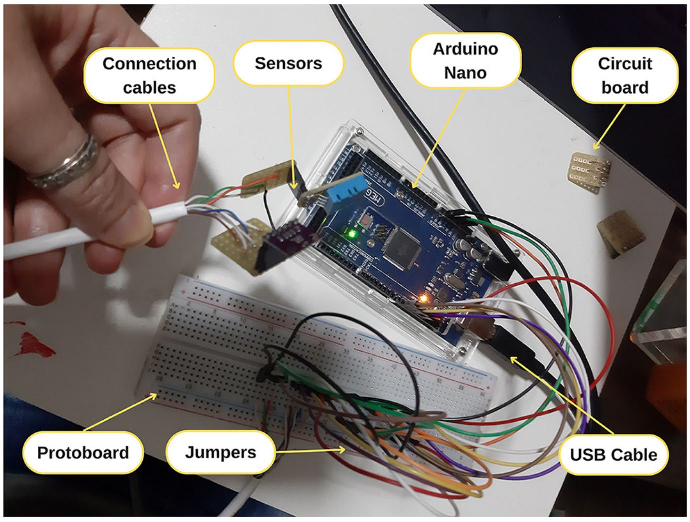

Figure 5 - Arduino Communication and Sensors in the Ventilation Circuit.

The circuit diagram was designed using the Fritzing® software (Fritzing, 2022) (Figure 6). The verification step (PDCA cycle) includes programming each circuit's component to acquire the data, using its Arduino specific library, and testing the data reading of each sensor.

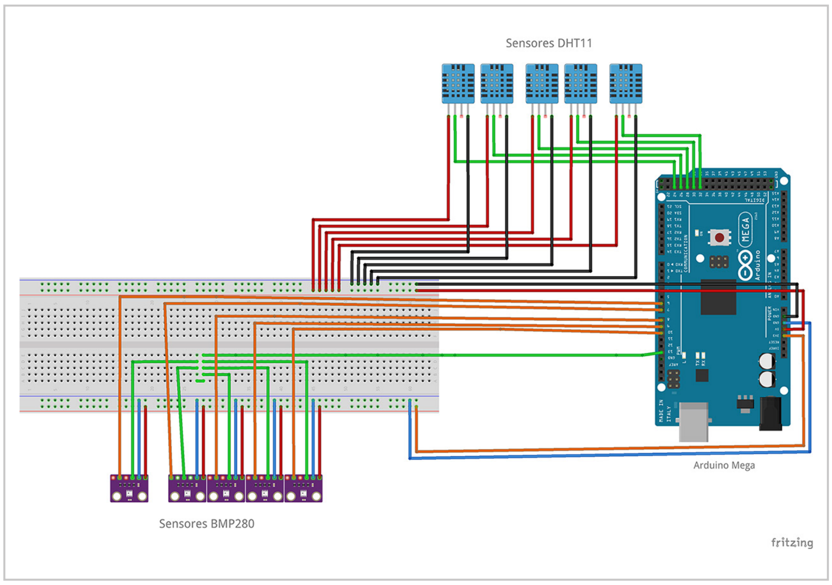

Figure 6 - Assembly of the ventilation circuit in Fritzing ® (Fritzing, 2022).

Figure 7 shows the modular lab setup with the tubes, connections, sensors, and corresponding individual wiring that connects them to the Arduino.

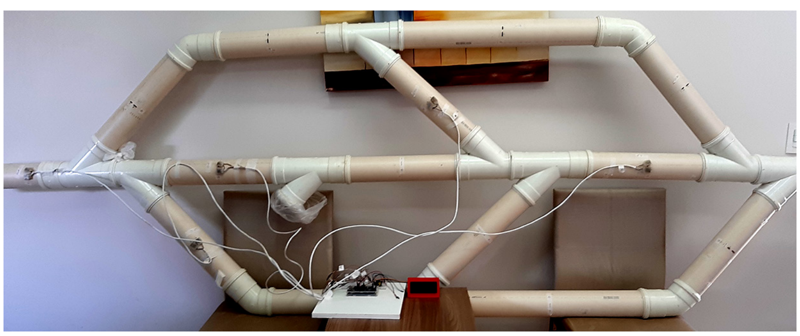

Figure 7 - Connection of sensors to Arduino.

Each PVC segment contains the DHT11 and BMP280 sensors located inside the ducts that can be easily connected and disconnected (Figure 8). It guarantees flexibility and safe transportation, in addition to facilitating the assembly of the circuit in other environments, such as classrooms, fairs and technical presentations.

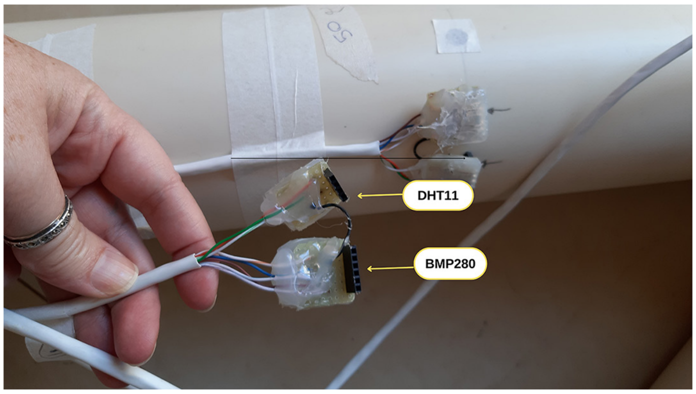

Figure 8 - Sensors connections.

A TESTO 425 hot wire anemometer, for measuring the air velocity, can be set up in eyelets close to the sensors. Figure 9 (a and b) represents the positioning of the sensors and anemometer externally and internally, respectively.

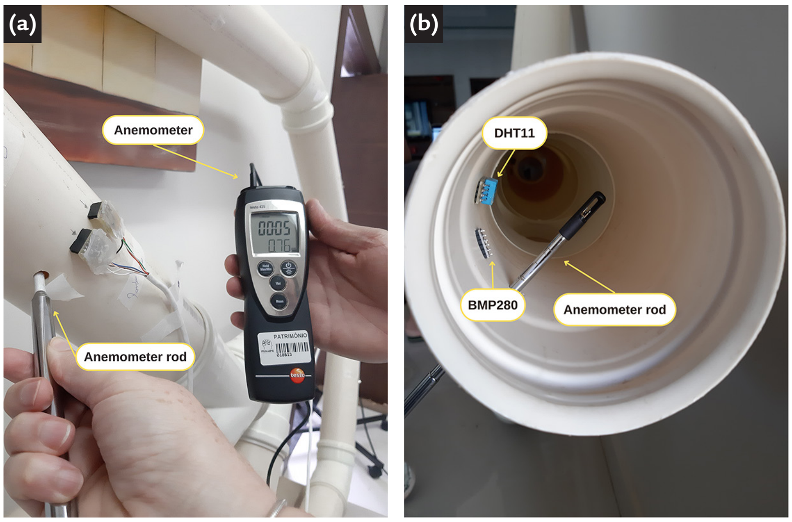

Figure 9 - Position of sensors and anemometer: (a) external and (b) internal.

When positioned in an eyelet, the hot wire anemometer continuously reads the air velocity for one minute. The algorithm, then, calculates the average of the values in that reading period. All data acquired, processed by the Arduino, can be transferred to a computer for later analysis. The system is capable of reading airflow velocity, pressure drop and resistance, allowing a faster analysis of the data.

By being modular, the numerous laboratorial scenarios can be designed, which include important experiments for understanding the behavior of the air with some variations, such as heat, humidity, resistance, and velocity. Suggested experiments for academic practices to highlight the relationships among the ventilation variables have been identified in the study:

- measurements of the air velocity inside the ducts and its behavior by modifying the circuit by closing the airways (barriers);
- measurements of the air velocity inside the ducts and its behavior modifying the fan pressure;
- measurements of air velocity inside the ducts and its behavior by modifying the walls of the circuit (roughness, for example);
- measurements the temperature of the environment (circuit) by modifying the flux velocity;
- measurements of the pressure difference inside the ducts;
- measurements of pressure loss and its behavior by modifying the circuit by closing ducts (barriers);
- measurements of humidity along the circuit;
- calculation of required flow, pressure loss and resistance by capturing data;
- generation of curves of measurement points of the items mentioned as a function of time;
- assembly of scenarios according to the selected circuit.

Figure 10 shows the circuit created with several possible scenarios depending on the chosen air passage closure. Thus, providing different possible behaviors. This figure represents the airflow in the straight pipe, as schematically demonstrated in Ventsim (Figure 3). This scenario makes it possible to study the behavior of the airflow at the beginning and at end of the circuit.

Figure 10 - Laboratory Scenario - straight pipe.

Figure 11 shows a straight tube installed in the ventilator and the sensors BMP280 and DHT11. All data transmitted by the Arduino and the computer can use the Microsoft Excel® software as an interface for data storage and subsequent analysis. The project uses the Arduino microcontroller to read sensors and store the data read in real time. The interface between the microcontroller and the sensors was developed using the Arduino IDE (Integrated Development Environment).

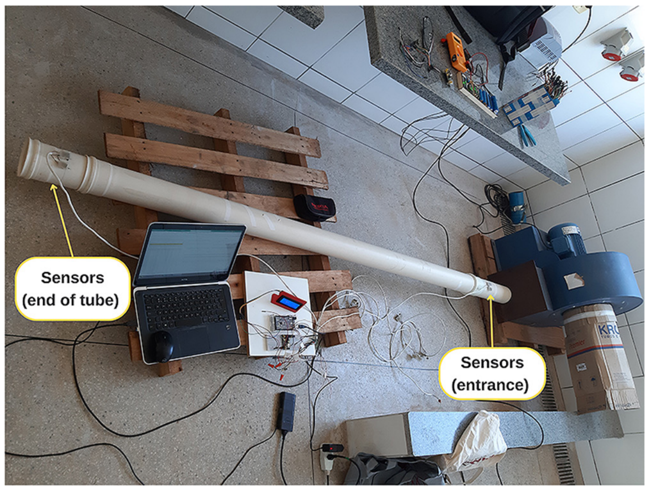

Figure 11 - Test circuit assembly.

Table 1 shows the average measurements at the beginning and end of the circuit presented in Figure 11 for 35 minutes and 20 seconds. The straight circuit (PVC Tube) has 2.5 meters, and a diameter of 100 mm. The airflow velocity, in meters per second (m/s), was defined using a thermal anemometer (TESTO 425). Readings related to pressure (hPa), temperature (°C) and relative humidity are averages of data collected every 7 seconds.

Table 1 - Variables readings in a straight PVC tube.

Point	V (m/s)	T (°C)	P (hPa)	RH (%)
Main entrance	8.72	39.5	918.04	21
End of tube	5.88	38.32	917.86	27

In this first scenario, a loss of speed can be observed along the circuit. Pressure losses occur proportionally to the increase in tube length. The results obtained were consistent with literature, requiring future comparisons regarding the lengths of the circuit and the material used to represent the galleries, in this case, PVC pipe with a diameter of 100 mm.

The system's construction costs vary according to the design, circuit size, number of curves, required accuracy, and consequently, the number of sensors. This analysis is essential to get the exact value of this investment. Table 2 shows the main items purchased and their respective values in January/2023 for the assembly of the modular ventilation laboratory circuit.

Table 2 - Main items acquired for the laboratory.

Components	Quantity	US$ total
Sensor DHT11	10	27.20
Sensor BMP280	10	21.00
Arduino Mega	2	88.42
Tubes and connections (PVC)	1	55.20
Cables (meters)	30	12.00
Circuit board	20	4.00
Protoboard	2	6.38
Jumpers	20	2.35
Total (US$)		**216.55**

The last stage of the PDCA cycle (action) is related to conducting the process according to the positive results already achieved in the previous stages, searching for continuous improvements to turn the process more efficient.

4. Discussion and conclusions

This playful methodology encourages creative and critical thinking to solve problems, in this article focused on modeling ventilation circuits in underground mines. Developing the ability to analyze and diagnose a problem situation and generation a solution, this skill being highly valued today.

The modular ventilation laboratory was designed for educational purposes. It allows the development of academic experiments using sensors for automatic acquisition of airflow velocity, temperature, humidity and pressure and data analysis for verifying concepts related to fluid mechanics and ventilation in underground mines. The low-cost construction of a technical work environment model encourages the use of teaching methodologies aimed at learning by doing.

The methodology using sensors (integrated into the system) makes the project dynamic and interactive, allowing for the simulation of some environments and studying the behavior of the parameters present in the project. The laboratory´s assembly character facilitates its disassembly and transport, thus allowing greater flexibility in storage and application. The suggested experiments point to different assembly possibilities, showing flexibility for equipment, investment, and available space. The monitoring results in the scenarios will be tested in the future in an educational environment, analyzing the results of the sensors in the modules and the use of hot wire anemometers.

The combination of theory and practice allows the evolution of knowledge and favors the visualization and assimilation of concepts. The work approaches the assembly of the didactic ventilation circuit, as future research suggests simulation with different speeds, setting up scenarios to test the circuits at the university and creating an interface to transform data into information. A schematic design of a circuit scenario was developed and presented in Ventsim, allowing simulations to be carried out in the future according to the physical scenario created during laboratory practices, allowing back-analysis to validate models using the Ventsim® software.

Acknowledgments

The authors thank the Graduate Program in Metallurgical, Materials and Mining Engineering (PPGEM) and Federal University of Minas Gerais (UFMG). The authors also thank the Federal University of Ouro Preto and FAPEMIG.

References

ALAM, I. I. Designing experiential learning projects for teaching marketing courses. ***Atlantic Marketing Journal***, v. 3, n. 3, p. 8, 2014.

ALVARENGA, J. F. Estudo dos índices operacionais da lavra subterrânea no Brasil. 2012. 71 f. Dissertação (Mestrado em Engenharia Mineral) - Universidade Federal de Ouro Preto, MG, 2012.

BHUTTA, K. S.; HUQ, F. Benchmarking - best practices: an integrated approach. ***Benchmarking Benchmarking an International Journal***, v. 6, p. 254-268, 1999.

BOULD, D.; Feletti, G. ***The challenge of problem - based learning.*** Kogan Page, London, 2017.

CAMPOS, V. F. ***Gerenciamento da rotina do trabalho do dia-a-dia.*** Nova Lima, MG: INDG Tecnologia e Serviços Ltda., 2004. 266 p.

COSTA, J. C. A. ***Estudos para implantação de um modelo de ventilação sob demanda no complexo mineiro de Ipueira-Ferbasa, município de Andorinha, Bahia.*** 2017. 111 f. Tese (Doutorado). Universidade Federal de Campina Grande, Paraíba. Brazil. 2017.

COSTA, L. de V.; SILVA, J. M. da. Strategies used to control the costs of underground ventilation in some Brazilian mines. ***REM - International Engineering Journal,*** Ouro Preto, v. 73, p. 555-560, 2020.

DEMING, W. E. The new economics, for industry, government, education, 2. ed. Cambridge, MA, USA: MIT Press, 2000. 240 p.

DZIURZYŃSKI, W.; KRACH, A.; PAŁKA, T. Airflow sensitivity assessment based on underground mine ventilation systems modeling. ***Energies,*** v. 10, 1451. 2017. DOI: https://doi.org/10.3390/en10101451

FRITZING software. Available online: Available at: https://fritzing.org/ Accessed at: 07 jul. de 2022.

GHOSH, S.; MANDAL, M.C.; RAY, A. A PDCA based approach to evaluate green supply chain management performance under a fuzzy environment. ***International Journal of Management Science and Engineering Management.*** p. 1-15, 2022. DOI: https://doi.org/10.1080/17509653.2022.2027292

LEGO Iconic: everything is impressive: a search and find celebration of LEGO® history. Buster Books, October, 2021. 32 p. ISBN-13: 978-1780557892

MCPHERSON, M. J. Subsurface ventilation and environmental engineering. *In*: ***Subsurface ventilation and environmental engineering***. Springer, 1993. 905 p. DOI:https://doi.org/10.1007/978-94-011-1550-6

NEME, M. B.; CURI, A.; SILVA, J. M.; CARNEIRO, A. C. B. Realização de projeto de lavra de mina subterrânea com utilização de aplicativos específicos. ***REM - Revista Escola de Minas***, v. 64, p. 519-524, 2011.

PEINALDO, J.; GRAEML, A. R. ***Administração da produção***: operações industriais e de serviços. Curitiba: UnicenP, 2007. p. 201-202.

PHAM EVANS, M. T.; TISAK, D. J.; WILLIAMSON, D. F. Twenty-first century benchmarking: searching for the next generation. ***Benchmarking: an International Journal***, v. 19, n. 6, p. 760-780, 2012.

RIBEIRO, L. R. C. ***A aprendizagem baseada em problemas (PBL)***: uma implementação na educação em engenharia na voz dos autores.2005. 209 f. Doctor Tese (Doutorado) - Universidade Federal de São Carlos - UFSCar, São Paulo, Brasil. 2005.

SANGPIKUL, A. Implementing academic service learning and the PDCA cycle in a marketing course: contributions to three beneficiaries. ***Journal of Hospitality, Leisure, Sport & Tourism Education***, v. 21, p. 83-87, 2017.

SANTOS, R. C. P.; SILVA, J. M.; OLIVEIRA, M. M.; MAZZINGHY, D. B. Simulation and models in pedagogical practices as a learning method: underground mining. *In*: BRAZILIAN CONGRESS ON OPEN PIT AND UNDERGROUND MINES, 10, 2021. [***Proceedings…***]. Belo Horizonte. Brazil. 2021.

SANTOS, R. C. P. ***Desenvolvimento de soluções de baixo custo para monitoramento de minas subterrâneas e de laboratório de ventilação utilizando a internet das coisas.*** Tese (Doutorado) - Universidade Federal de Minas Gerais, Belo Horizonte, Brasil. 2020.

SANTOS, R. C. P.; DA SILVA, J. M.; JUNIOR, W. A.; PINTO, C. L. L.; OLIVEIRA, M. M.; MAZZINGHY, D. B. Development of a low-cost device for monitoring ventilation parameters (Temperature, Humidity and Pressure) in underground environments to increase operational safety using IoT. ***Mining***, v. 2, p. 746-756. 2022. DOI: https://doi.org/10.3390/mining2040041

SELEME, R.; STADLER, H. ***Quality control***: the essential tools. 2. ed. Curitiba: Editor IBPEX. 2010. 184p.

SHEWHART, W. A. ***Economic control of quality of manufactured product.*** New York, NY, USA: Martino Fine Books, 2015. 516 p.

SILVA, J. M.; SANTOS, R. C. P.; S ILVA FILHO A. O. Expansion of human resources and infrastructure in mine ventilation in Brazil. *In*: INTERNATIONAL SYMPOSIUM IN MINE VENTILATION OF SOUTH AMERICA, 2, 2021. Lima, Peru.

SZLĄZAK, N.; KORZEC, M. The solution of the main fan station for underground mines being decommissioned in terms of reducing energy consumption by ventilation. ***Energies,*** v. 15, 2022. 4612. DOI: https://doi.org/10.3390/en15134612

VARADEJSATITWONG, P.; BANOMYONG, R.; JULAGASIGORN, P. A Proposed Performance-Measurement System for Enabling Sup-ply-Chain Strategies. ***Sustainability,*** v. 14, 2022. https://doi.org/10.3390/su141911797

VENTSIM 3D Mining Ventilation Simulation Software. Available at: https://ventsim.com/ Accessed at: 07 jul. de 2022.

XU, G.; HUANG, J.; NIE, B.; CHALMERS, D.; YANG, Z. Calibration of mine ventilation network models using the non-linear optimization algorithm. ***Energies,*** v. 11, 2018. DOI: https://doi.org/10.3390/en11010031

Received: 22 June 2023 - Accepted: 5 October 2023.