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Designing a Smart System for Predicting Carbon Dioxide Emissions from Traditional Wood-Fired Heating in Homes During the Winter Season

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Abstract

Carbon dioxide (CO2) poses a significant health hazard in homes, particularly during winter when traditional heating methods, such as wood burning, are prevalent. These methods often lead to elevated CO2 levels, increasing the risk of respiratory issues and even fatalities. To address this critical concern, we introduce a novel ventilation system designed to effectively regulate CO2 levels and ensure a safe indoor environment. The system comprises a CO2 sensor, a temperature sensor, a fan, a yellow light indicator, and an automatic window opener. It operates under two scenarios: Scenario 1**:** Mechanical ventilation only: The fan operates to circulate air within the room when CO2 levels reach a predetermined threshold and the outdoor temperature is less than 17°C. Scenario 2**:** Combined mechanical and natural ventilation: The fan operates, and the window automatically opens when CO2 levels reach the threshold and the outdoor temperature is higher than 17°C. A computational simulation was employed to realistically depict the system's operational concept. The simulation tracked both carbon dioxide (CO2) movement within the room and the system's response to predefined CO2 concentration thresholds established by European regulations. The simulations demonstrate the system's effectiveness in reducing CO2 levels to safe limits within a reasonable timeframe. The simulations also highlight the benefits of combined mechanical and natural ventilation in optimizing energy efficiency and maintaining comfortable indoor temperatures. The proposed ventilation system offers a promising solution to mitigate the health risks associated with elevated CO2 levels in homes, particularly during winter when traditional heating methods are employed. Its adaptability to varying CO2 concentrations and external temperatures ensures a safe and comfortable indoor environment.

Keywords

CO_2 Emissions, Wood-Fired Heating, Emotional intelligence, Machine Learning, Predicting, Sustainability

1. Introduction

Saudi Arabia faces significant indoor air quality challenges, particularly during the winter due to the widespread use of traditional wood-fired heating systems. This issue is intensified by population growth and urbanization, which contribute to rising CO2 emissions in residential areas. In alignment with Vision 2030's goal of transforming Saudi Arabia into a "Green Saudi" through substantial reductions in carbon emissions, this project proposes the development of a smart system to predict and manage CO2 emissions from these traditional heating sources (*Information About Saudi Green Initiative*, n.d.). The research underscores the health risks associated with CO2 and particulate emissions from wood heating, including respiratory infections and increased cancer risks (Pandey et al., 1990; Bari et al., 2011). Furthermore, initiatives by the European Commission aim to foster a CO2-emission-free society by integrating smart energy systems, and enhancing energy efficiency (Bari et al., 2011). Similar efforts in China's developing regions involve adopting smart infrastructure to facilitate sustainable urban development and reduce CO2 emissions (Guo et al., 2022). Studies in the United States highlight the considerable contribution of residential wood heating to national CO2 emissions, suggesting a need for optimized combustion and reduced emissions (Marin et al., 2022; Ahmadi et al., 2020). The type of wood and its moisture content are crucial factors affecting emission levels, pointing to the benefits of using well-dried wood for more efficient burning (Morin et al., 2022). Additionally, wood burning significantly contributes to the presence of harmful pollutants like PAHs and oxy-PAHs in the environment, with exposure levels correlating with population density and urbanization levels (Lim et al., 2022). These findings collectively emphasize the importance of developing advanced, efficient, and cleaner heating technologies to mitigate health risks and environmental impact. In addressing these pressing concerns, our research aims to provide a proactive solution through the implementation of a smart system for predicting and managing CO2 emissions from traditional wood-fired heating systems in Saudi homes. By leveraging advanced sensors, microcontroller technology, and emotional intelligence which has come to be widely recognized as a key component in our overall well-being and success (Dhiman, 2017), our system seeks to enhance indoor air quality and reduce the environmental footprint associated with conventional heating practices. research indicates that the efficiency of mechanical ventilation can be affected by the temperature difference between indoor and outdoor environments. At temperatures below 17°C, the heating load required to maintain comfortable indoor temperatures increases significantly when windows are opened for natural ventilation (Sekartaji et al., 2023). Therefore, limiting the use of natural ventilation (opening windows) when the outdoor temperature is below 17°C can help reduce the energy consumption associated with heating. Studies have shown that natural ventilation can be effectively used to maintain comfort without excessive energy use when the outdoor temperature is within a certain range (Bayoumi, 2018). The 17°C threshold may represent a balance between providing adequate ventilation for CO2 removal while maintaining thermal comfort without the need for additional heating.

2. Area of Study

This project focuses on the geographical region of the Kingdom of Saudi Arabia (KSA), the largest country in the Middle East, spanning approximately two million square kilometers, as depicted in Figure 1. Geopolitically, the KSA shares borders with various neighboring countries. Its northern border is shared with the Republic of Iraq and Jordan, while Kuwait lies to the northeast. To the east, it borders Qatar and the United Arab Emirates. Furthermore, the Kingdom of Bahrain is linked to the KSA via the King Fahd Causeway. Down south, it shares borders with Yemen and the Sultanate of Oman to the southeast. Its western frontier is marked by the Red Sea. Currently, the KSA comprises 13 administrative regions, each further subdivided into varying numbers of governorates. The KSA's climate during winter varies across regions due to its vast expanse and geographical diversity. In general:

i. The northern and central regions, including Riyadh, experience a moderate to cold climate with daytime temperatures ranging from 14°C to 22°C and nighttime temperatures dropping to 0°C to 5°C.
ii. The western and southwestern highlands, encompassing cities like Jeddah and Mecca, enjoy mild and humid winters, with daytime temperatures ranging from 22°C to 28°C and nighttime temperatures not falling below 15°C. The Asir region experiences cooler weather with increased rainfall.
iii. The Eastern Region, including cities like Dammam and Al-Khobar, witness mild winters, with daytime temperatures ranging from 18°C to 24°C and sporadic rainfall.
iv. Even the desert areas, like the Empty Quarter, experience cooler temperatures in winter, with significant fluctuations between day and night temperatures.

Figure 1. The location of the Kingdom of Saudi Arabia and its administrative regions in 2024

3. The hypotheses of the study

To achieve the main objectives of the study, three hypotheses were formulated:
Hypothesis 1: The smart air renewal system will reduce CO2 in homes during winter using a two-stage approach optimized by external temperatures.
Hypothesis 2: SolidWorks 2022 for mechanical modeling and CO2 simulation, combined with Proteus for electrical validation, will ensure the system's design accuracy and reliability.
Hypothesis 3: A visual simulation will enhance user understanding of the smart air renewal system's functionality.

This study aims to achieve the following:

- Designing a smart system to predict CO2 emissions from traditional wood-fired heating appliances in homes during winter to safeguard user health and the environment.
- Developing a sustainable strategy to reduce carbon emissions from wood-fired heating appliances, aligning with KSA's environmental and health sustainability goals.
- Analyzing the effects of reducing carbon emissions on the health of users dependent on wood-fired heating appliances and offering recommendations to enhance indoor air quality and mitigate associated health risks.

4. Research Methodology

Emotional intelligence and machine learning are pivotal in this research, as they contribute to the development of a proactive machine learning model aimed at addressing indoor air quality challenges. The system incorporates CO2 sensors, ventilation controls, EI-based lighting systems, and micro-control technology to pave the way for a smarter and greener future in residential heating, as depicted in Figure 2.
Utilizing a two-stage air regeneration and emissions management strategy that adjusts based on outside temperature conditions. Through the incorporation of sensors, emotional intelligence, and precise control technology, safety and comfort during winter are ensured. The system utilizes a CO2 gas sensor, MH-Z19B, employing non-dispersive infrared (NDIR) technology for accurate air detection. Arduino microcontrollers monitor environmental parameters and implement control logic for the heating system based on sensor inputs.

Mechanical modeling is executed using SolidWorks 2022, creating a virtual model to simulate the heating system's operation. Electronic circuit design and simulation are facilitated through Proteus software for the smart system.
An algorithm flowchart is developed to monitor and control indoor air quality based on CO2 levels and temperature, promoting adaptive air quality management, as depicted in Figure 3.

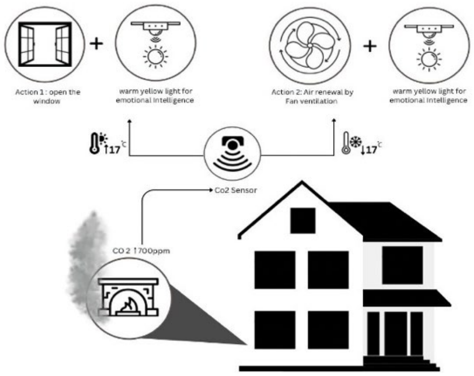


Figure 2. Designing a Smart System for Predicting Carbon Dioxide Emissions from Traditional Wood-Fired

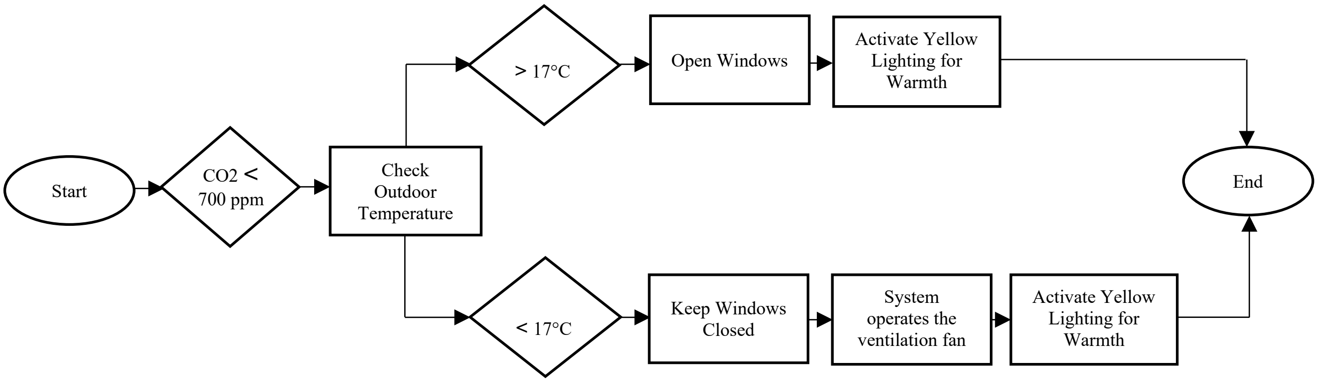


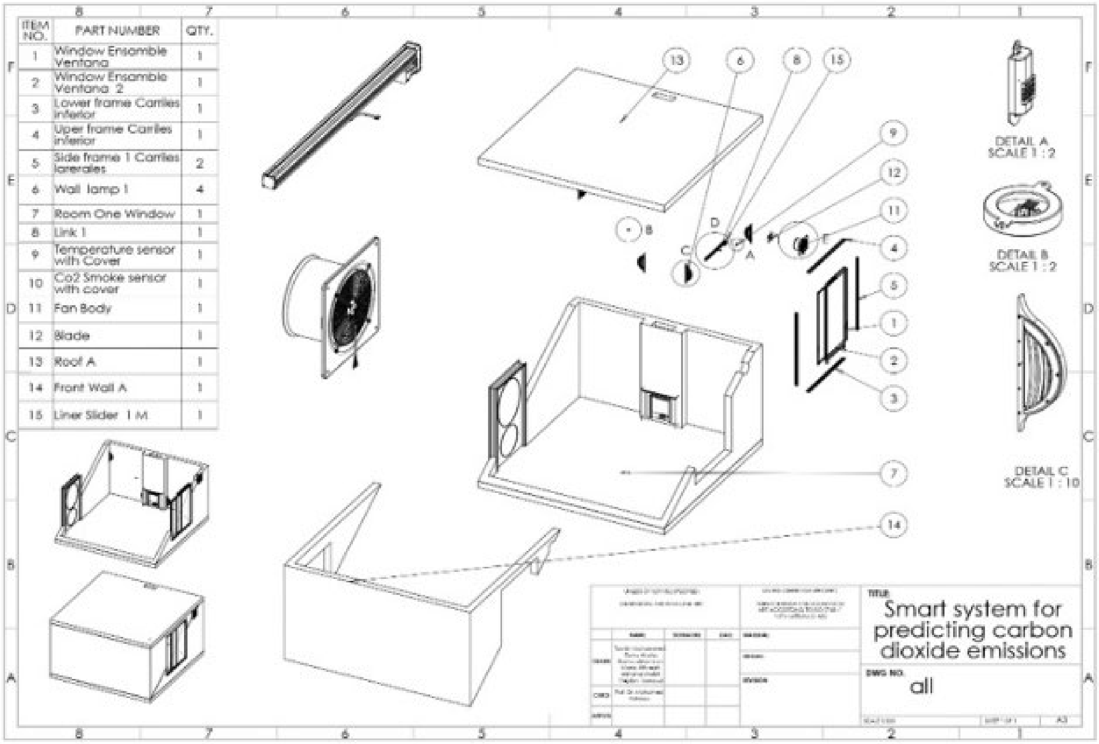
Figure 3. Algorithm Flowchart of the system's working

5. Data Collection

Data used in this research have been collected from various sources such as the World Health Organization, SolidWorks Simulation, and Proteus Simulation. SolidWorks allows to creation of a virtual model that provides insights into the heating system and simulates its operation under various conditions. This includes modeling the combustion process of the wood, the heat transfer within the system, and the emission of carbon dioxide. Proteus can be used in circuits for designing and simulating the electronic circuits that are part of the smart system. This includes the circuits for sensors that monitor temperature and carbon dioxide levels and control circuits for managing the heating system. Proteus also consists of a visual designer tool for Arduino. This allows for the rapid prototyping of systems. Where we utilized Proteus, as shown below, to simulate the electrical circuit of the system, ensuring accuracy and efficiency in our analysis.

6. Computer-Aided Design (CAD)

We used the SolidWorks program to design the project pieces (Montazeri et al., 2024; Earl et al., 2005), due to our experience in it, as it was one of the courses studied during our journey in industrial engineering, and for the efficiency and accuracy of the program, as well as the possibility of performing simulations using it. Therefore, it was the most appropriate choice for our project. We explained the design stages for all the parts until the project's final design, as shown in Figure 4.



ITEM NO.	PART NUMBER	QTY.
1	Window Ensamble Ventana	1
2	Window Ensamble Ventana 2	1
3	Lower frame Carriles inferior	1
4	Uper frame Carriles inferior	1
5	Side frame 1 Carriles lareralles	2
6	Wall lamp 1	4
7	Room One Window	1
8	Link 1	1
9	Temperature sensor with Cover	1
10	Co2 Smoke sensor with cover	1
11	Fan Body	1
12	Blade	1
13	Roof A	1
14	Front Wall A	1
15	Liner Slider 1 M	1

Figure 4. Assembling parts using SolidWorks

7. Simulation

Smart homes are perceived as a promising solution for providing support to inhabitants in completing daily activities, prolonging independence, and enhancing the quality of life. Achieving efficient simulation would indeed make smart system design feasible concerning several limitations such as cost, time, and inflexibility of smart homes. The limitations also extend to both the limited quality and quantity of existing sensor datasets. Smart home simulation is identified as a potential solution to mitigate these limitations (Ho et al., 2019). Simulation is a key phase in the design and verification process of a system, as it heavily impacts time-to-market and the competitiveness of the final product. In this context of design, simulation is a very critical task, as each domain of components adopts specific tools and frameworks (Franco Fummi et al., 2014).

7.1 Solid Works Simulation

SolidWorks Simulation is an essential tool in the design of a smart system for predicting CO_2 It enables the design and optimization of the system, contributing to a more sustainable and environmentally friendly heating solution. In the context of our project, SolidWorks Simulation allows to creation of a virtual model that provides insights into the heating system and simulates its operation under various conditions. This includes modeling the combustion process of the wood, the heat transfer within the system, and the emission of CO_2. This information can be used to optimize the design of the system to minimize CO_2 emissions and improve efficiency.

7.1.1 Enhancing CO2 Reduction and Energy Efficiency in Homes with Visual Simulation

Visual simulations serve as graphic tools utilized to portray the anticipated outcomes of proposed projects. This includes photo simulations, video simulations, and immersive 3D models. These simulations provide an accurate depiction of how a project would be perceived from various perspectives.

The detailed simulation of the system's operation:

i. A comprehensive simulation of the entire system and its operation was conducted visually using video and 3D models for the Whole room (see Figure 5 and Figure 6) and the operations included.

ii. The system initiates when the firewood ignites, and a CO_2 sensor (see Figure 7) automatically measures the CO_2 emissions level in the room.

iii. If this level is below or equal to 700 parts per million (ppm), the system takes no action.
iv. However, if the level exceeds 700 ppm, the system responds based on the outdoor temperature.
v. When the outdoor temperature is above 17 degrees Celsius (see Figure 8), the system opens the windows for ventilation (see Figure 9 and Figure 10) and activates the yellow lights to provide warmth (see Figure 11).
vi. Conversely, when the outdoor temperature is below 17 degrees Celsius, the system operates the ventilation fan (see Figure 12) and activates the yellow lights to provide warmth inside the room.

It should be noted that we have determined the allowable CO_2 emissions level based on studies provided by the World Health Organization.

Simulation Steps:

i. Simulate the Room

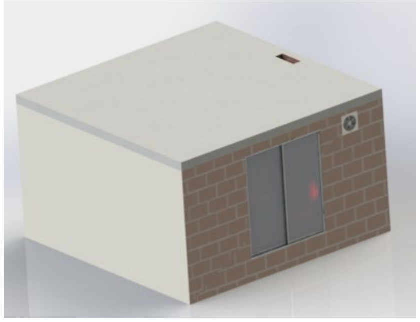


Figure 5. Simulation 3D Model of the Room from outside.

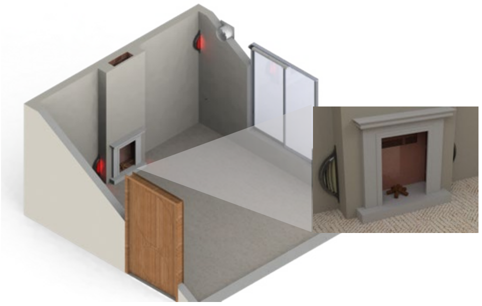


Figure 6**.** Simulation 3D Model of the Room from inside.

ii. Simulate the Carbon Dioxide (CO_2)

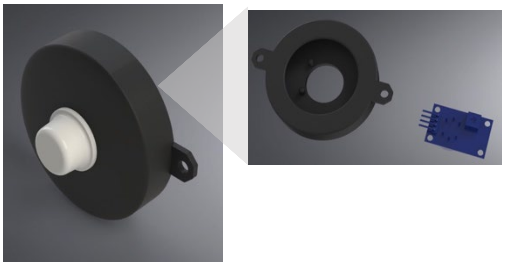


Figure 7**.** Simulation 3D Model of The CO2 sensor.

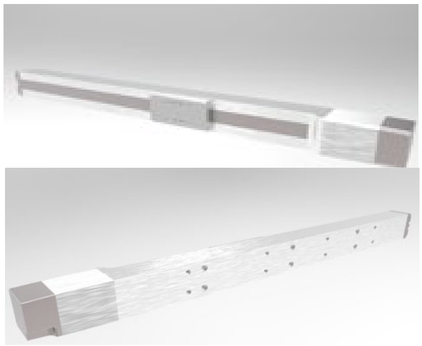


Figure 8. Simulation 3D Model of the window from the front and back.

iii. Simulate The Temperature

Figure 9. Simulation 3D Model of the temperature sensor.

iv. Simulate the Window and Window Slider

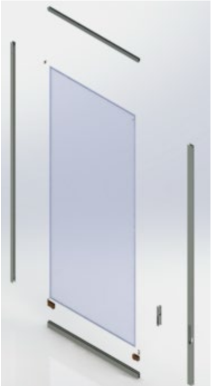


Figure 11. Simulation 3D Model of the window.

v. Simulate The Yellow Lights

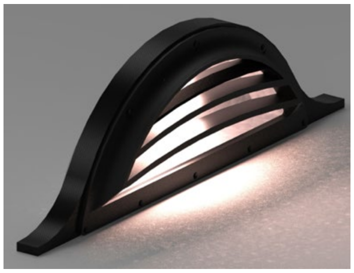


Figure 10. Simulation 3D Model of the yellow lights

vi. Simulate The Fan

Figure 12. Simulation 3D Model of the fan

7.2 Proteus Simulation

Proteus is a simulation and electronic design development tool. It is a very useful tool as it ensures that the circuit design is working properly before beginning to physically work on it (Shah, 2024).

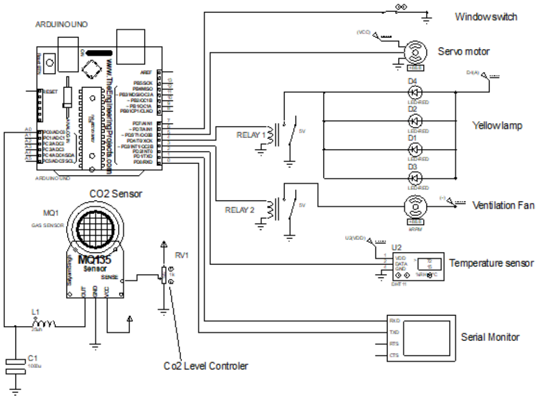


Figure 13. Simulation diagram of the smart system on Proteus

In the context of designing a smart system for predicting CO_2, Proteus provides a comprehensive platform to simulate and analyze the to create virtual models of the heating system and its components. Proteus can be used in circuits for designing and simulating the electronic circuits that are part of the smart system. This includes the circuits for sensors that monitor temperature and carbon dioxide levels and control circuits for managing the heating system (Figure 13). Proteus also includes a visual designer tool for Arduino. This allows for the rapid prototyping of systems. Where we utilized Proteus, as shown below, to simulate the electrical circuit of our system, ensuring accuracy and efficiency in our analysis.

7.2.1 Arduino IDE Code with Explanation:

Arduino is an open-source electronics platform featuring microcontroller boards and an Integrated Development Environment for programming (Badamasi, 2014). In the context of designing a smart system for predicting CO_2, Arduino IDE works enabling sensor circuits to accurately monitor environmental parameters like temperature and CO_2 levels. With Arduino's microcontrollers, control circuits execute algorithms to manage heating systems based on sensor inputs, regulating elements and ventilation for optimal indoor conditions. Its compatibility with various electronic components facilitates seamless integration with smart devices, allowing the simulation of interactions with thermostats, and actuators. Writing code in Arduino IDE is crucial (Figure 14), as it governs system behavior, from sensor data acquisition to control logic for actuators through the simulation tool Proteus. Here is how to write the code in Arduino:

```
  // If the CO2 level is higher than 700 ppm, turn on the mechanical
ventilation
  if (co2_ppm >= 700) {
    digitalWrite(RELAYPIN, HIGH);

    // If the temperature is higher than 17 degrees and the window is
closed, open the window and turn on the lamp
    if (temperature >= 17 && digitalRead(WINDOW_SWITCH_PIN) == LOW) {
      windowServo.write(90);
      digitalWrite(LAMP_PIN, HIGH);

      // While the CO2 level is higher than 700 ppm, keep reading the
MQ135 sensor
      while (co2_ppm >= 700) {
        int mq135SensorValue = analogRead(MQ135PIN);
        float voltage = mq135SensorValue * (5.0 / 1023.0);
        int co2_ppm = map(voltage, 0, 5.0, 0, 1000);

        // If the CO2 level is lower than 400 ppm, close the window and
turn off the lamp
        if (co2_ppm <= 400) {
          windowServo.write(0);
          digitalWrite(LAMP_PIN, LOW);
          break;
        }

        // Print the CO2 level and the temperature
        Serial.print("Co2_ppm: ");
        Serial.println(co2_ppm);
        Serial.print("Temperature Degree: ");
        Serial.println(temperature);

        // Wait for 1 second before reading the sensors again
        delay(1000);
      }
    }
  } else if (co2_ppm <= 400) { // If the CO2 level is lower than 400
ppm, turn off the mechanical ventilation
    digitalWrite(RELAYPIN, LOW);
  }

  // Print the CO2 level and the temperature
  Serial.print("Co2_ppm: ");
  Serial.println(co2_ppm);
  Serial.print("Temperature Degree: ");
  Serial.println(temperature);

  // Wait for 1 second before reading the sensors again
  delay(1000);
}
```

Figure 14. Arduino IDE Code for the electrical circuit in the system

8. Analysis and Discussion

8.1 A Graphical Simulation Study Comparing Ventilation Systems for Reducing CO2 Emissions in Indoor Environments.

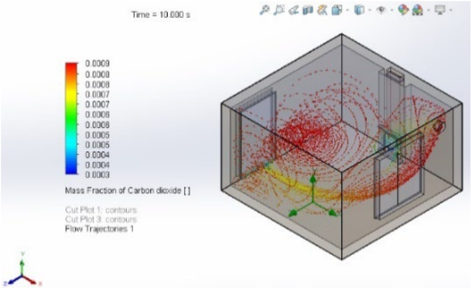
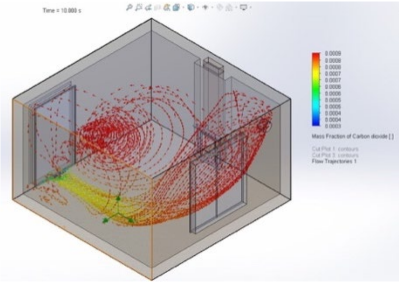
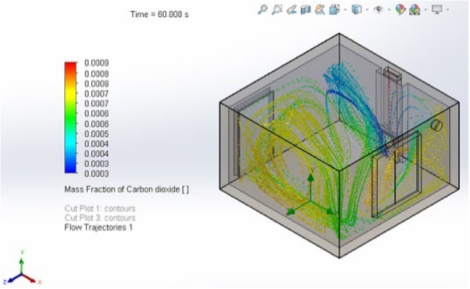
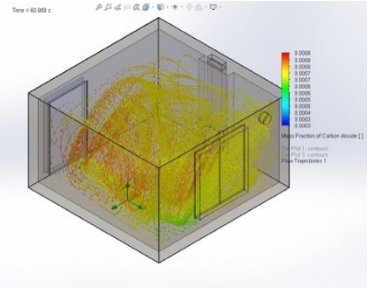
Through graphical simulation of the system's operation, we were able to monitor the quantity of CO_2 in two scenarios: when the window is open and the fan is running, and when the window is closed, and the mechanical system represented by the fan is operational. The simulation aims to determine the difference between regular mechanical systems, where only the fan is involved, and another system consisting of sensors and two ventilation systems: a mechanical one and a semi-automatic one represented by the automatic window. The following simulation illustrates the time required to expel CO_2 and reduce its quantity from 900 ppm to 400 ppm under the worst conditions, with a fire burning, in both scenarios Table 1 and Table 2:

i. Using only the fan and the window closed.
ii. Using both the fan and the window open.

As seen in the Cut Plots Table 2 for both scenarios, during the first 10 seconds, the dominant color is red, indicating high and unacceptable levels of carbon dioxide emissions at 900 ppm. Over time, the color changes, showing a decrease in the percentage of emissions. In the scenario where the window is open, by the 180th second, the color shifts entirely to blue, indicating that the CO2 emissions have reached a required level of around 400 ppm. However, in the second scenario where the window is closed, the emissions take 480 seconds, equivalent to 8 minutes, to reach the required level. Similar results are observed in the Flow trajectories plots Table 1 it's evident that it illustrates the direction of airflow and emissions. As depicted, clean air flows from beneath the door towards the fan and the window.

Additionally, within the Cut plots, it's evident that the emission levels inside the fireplace remain unchanged. This reaffirms the accuracy and realism of the simulation and its results.

Table 1. Cut plots

	Scenario	
Time	**Opened Window**	**Closed Window**
10 s		
60 s		

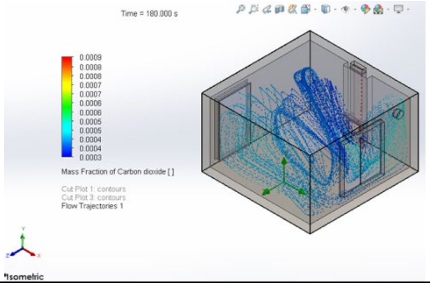
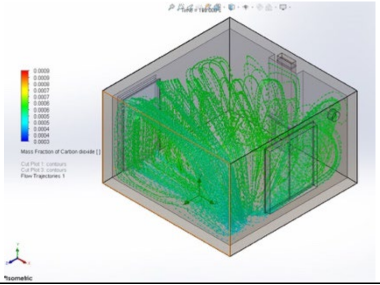
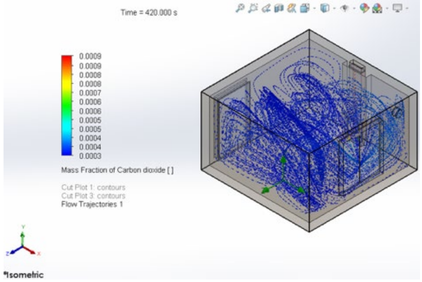
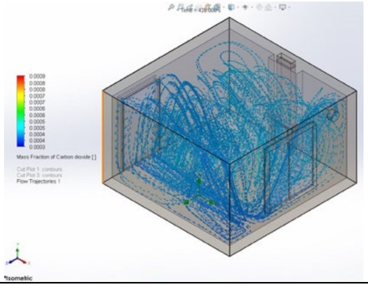
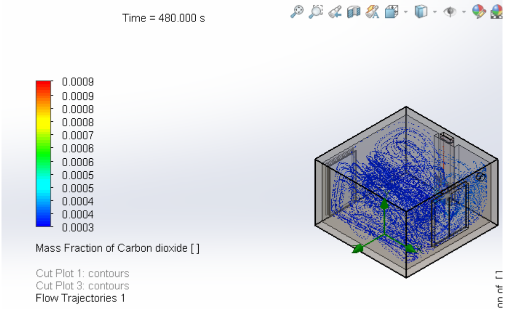
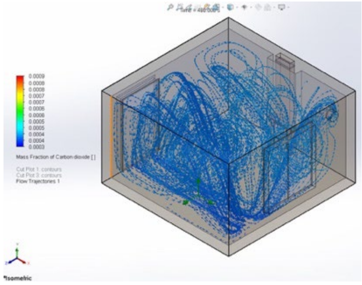
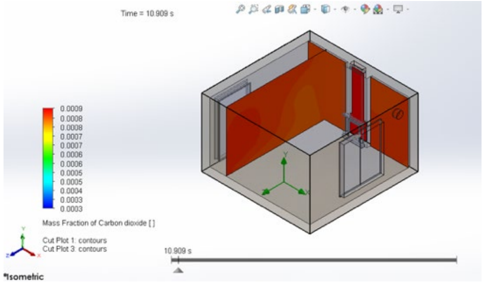
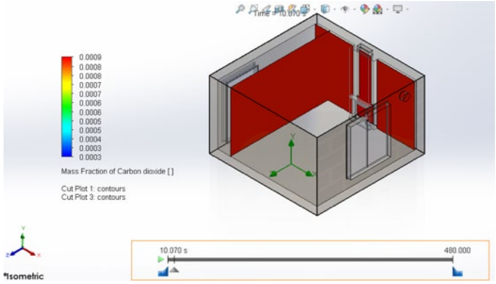
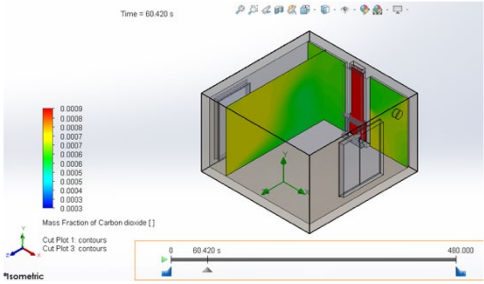
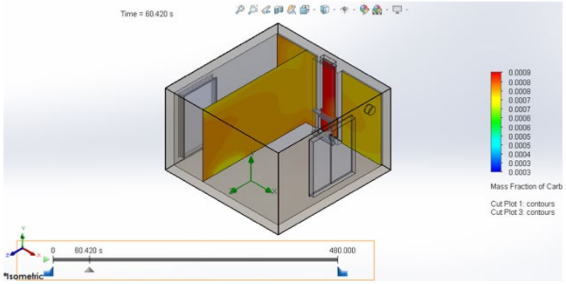
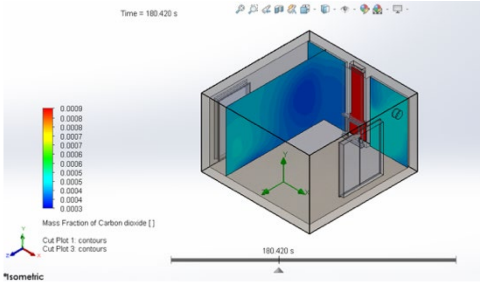
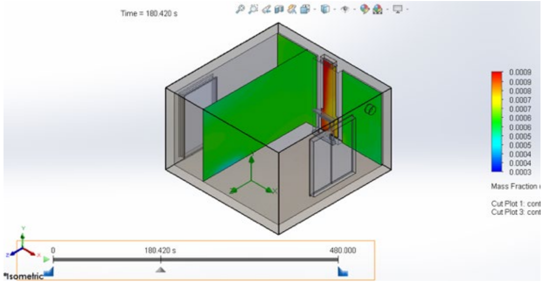
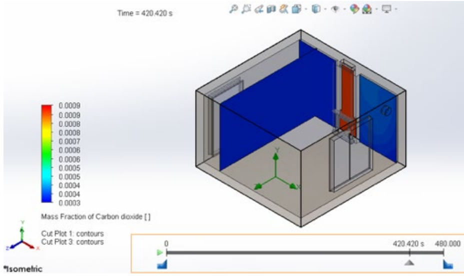
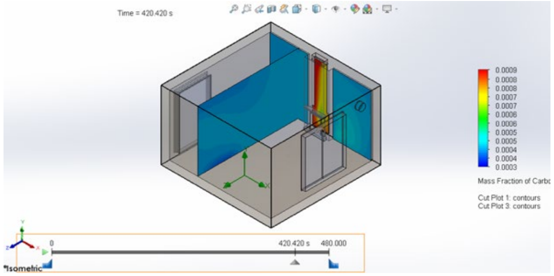
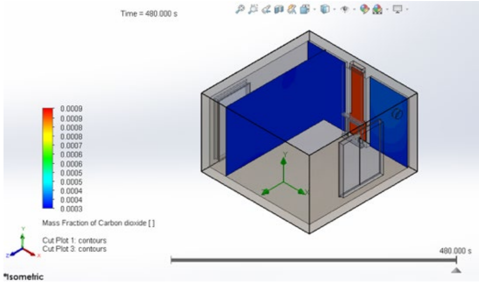
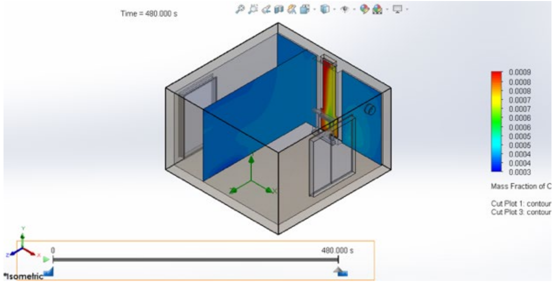
180 s		
420 s		
480 s		

Table 2. Flow trajectories plots

Scenario		
Time	**Opened Window**	**Closed Window**
10 s		

60 s		
180 s		
420s		
480 s		

8.2 Effect of Window Ventilation Systems on Air Quality and Energy Efficiency

The results of the graphical simulation show that the curve for the closed window scenario Figure 15 shows the mass fraction of CO_2 over time. Initially, the CO_2 concentration is high at 900 ppm during the first 10 seconds of system operation. Over time, the CO_2 levels gradually decrease until they reach 400 ppm after 480 seconds. In the open window scenario curve Figure 16, the CO_2 concentration also starts at 900 parts per second during the first 10 seconds. However, the decrease in CO_2 levels is more rapid. After 180 seconds, the CO_2 concentration reaches 400 ppm.

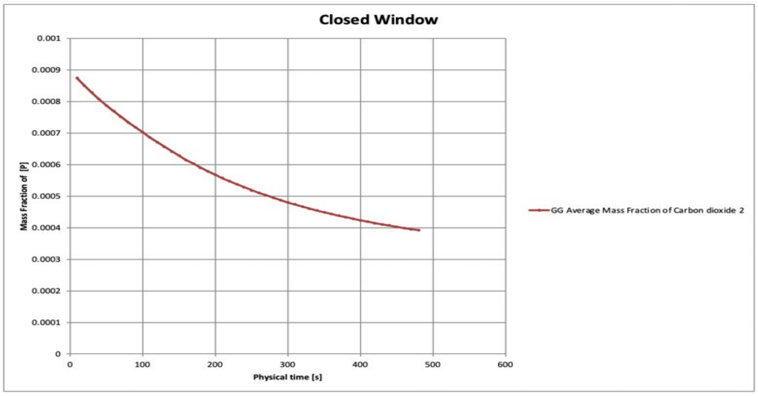


Figure 15. CO2 Average Mass Fraction Over Time in the closed window scenario.

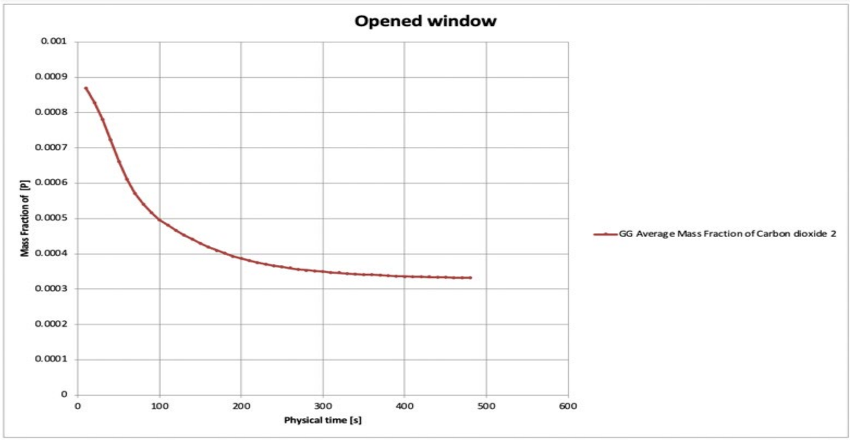


Figure 16. CO2 Average Mass Fraction Over Time in the opened window scenario.

In summary, the closed window system does not save as much energy compared to the open window scenario. opening the window led to substantial energy savings while maintaining acceptable CO_2 levels and better air quality, more than half of the time and more than half of the energy cost of operating the fan were saved, through the following equation:

Time for opened window = 180 s, time for closed window = 480 s,

$$Change = \frac{C - O}{C} = \frac{480 - 180}{480} = 0.625$$

at a rate of approximately 0.625. opening the window accelerates the reduction of CO_2 mass fraction, leading to improved indoor air quality and energy efficiency. The open-window approach appears to be more efficient in temperate climates. And that outdoor CO_2 levels typically range from 300 to 600 ppm, so opening windows can help maintain a healthy indoor environment (Heebøll et al., 2018).

8. Conclusion

This research introduces an intelligent system aimed at predicting and reducing carbon dioxide (CO2) levels in homes during winter, especially in areas with traditional wood-fired heating. Aligned with Saudi Arabia's Vision 2030 and European CO2 standards, the system employs a two-stage air renewal strategy adjusted according to external temperatures. Using SolidWorks 2022 for mechanical modeling and CO2 flow simulation, alongside Proteus software for electrical circuit verification, the system's efficacy was validated virtually. Results indicate significant CO2 reduction, enhancing indoor air quality and addressing health risks associated with CO2 accumulation. The system offers a sustainable solution for wood-heated homes and can integrate with existing heating systems affordably. Future research should explore AI and machine learning to optimize performance further to back up the conclusions and recommendations obtained from the first probations, further research will be conducted. Partnership with specialists and practical studies will be the amplifier that intensifies the understanding of the subject, consequently, improving the accuracy of this project`s representation, the study tries to go beyond the initial research and experiments and investigates some other features of the design. Through this exploration, we can reach a more detailed knowledge of how traditional wood-fired heating affects pollution levels, air quality, and the health of people. Promoting awareness and adopting smart heating technologies can lead to a healthier and more sustainable future, particularly in regions reliant on wood heating.

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Rasha A Al-Shamrani is an undergraduate student in her final year of industrial engineering at the University of Bisha She has consistently demonstrated exceptional academic performance throughout her undergraduate journey. She actively contributes to the activities and programs section at IEOM UB student chapter, she is an active member of the Public Relations and Organization Department, a project manager for hackathons and camps in the Engineering Club, a member of the Planning Committee of the Renewable Energy Club, and a member of the Construction Program to explain industrial engineering plan courses. She received cooperative training at the Southern Province Cement Company and training at the hackathons, which is an electronic platform that organizes competitions and challenges Locally, regionally, and globally. Rasha's research interests include data analysis, risk analysis, sustainability, continuous improvement, supply chains and logistics services, and Industry and environmental health.

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