

LabVIEW Based HVAC Building Management Energy Optimizer for Occupancy and Air-Quality Responsive Ventilation Control

Lokesh S¹, Sakthi Deepashika N², Dr.Saravanakumar R³

¹under Graduate Student, Vellore Institute Of Technology, Vellore

²under Graduate Student, Vellore Institute Of Technology, Vellore

³ Professor Higher Academic Grade, Vellore Institute Of Technology, Vellore

Abstract: Heating, ventilation, and air-conditioning (HVAC) systems contribute significantly to total building energy consumption because conventional ventilation systems often operate continuously at fixed power levels regardless of real-time spatial demand. This paper presents the design, hardware implementation, and graphical validation of a low-cost, real-time HVAC Building Management Energy Optimizer that dynamically regulates ventilation based on room occupancy and environmental sensing. The hardware architecture utilizes an ESP32 microcontroller as the central control unit, an HC-SR501 passive infrared (PIR) sensor for occupancy detection, an MQ135 analog environmental sensor, an L298N driver module for Pulse-Width Modulation (PWM) fan control, a 6 V DC geared motor representing the ventilation fan, and an SG90 servo motor serving as a motorized HVAC airflow damper. Laboratory Virtual Instrument Engineering Workbench (LabVIEW) communicates with the ESP32 via a USB serial (VISA) interface to provide graphical real-time data acquisition, parameter visualization, decision monitoring, and dynamic power/energy estimation. The system employs a rule-based control strategy where occupancy acts as the primary gate: when unoccupied, fan speed and damper position are set to 0% and 0°, respectively. Under occupied conditions, ventilation is scaled across three demand tiers—30% (30° damper), 60% (60° damper), and 100% (90° damper)—based on analog air-quality threshold boundaries. Experimental validation confirms the full hardware-software execution chain, establishing an accessible, transparent prototype for demand-controlled ventilation (DCV) and building energy optimization

Keywords: HVAC energy optimization, LabVIEW, ESP32, PIR sensor, MQ135, adaptive ventilation, L298N, servo damper, energy monitoring, building management system.

I. INTRODUCTION

Concrete and operational energy management in modern infrastructure both face substantial resource conservation challenges. In building management, heating, ventilation, and air-conditioning (HVAC) systems account for a major fraction of total electrical energy consumption. Traditional HVAC systems frequently rely on static operating schedules or continuous fixed-speed fan operation. This operational model causes significant energy waste during periods of low occupancy or when ambient indoor air quality satisfies health standards without maximum airflow. Demand-Controlled Ventilation (DCV) addresses these inefficiencies by modulating airflow according to real-time indoor environmental metrics and human

presence. By matching ventilation output directly to actual spatial demand, DCV significantly reduces fan power draw during low-demand periods while maintaining healthy indoor air quality when spaces are fully occupied.

This study presents a LabVIEW-based HVAC Building Management Energy Optimizer that combines embedded hardware control with graphical software monitoring. The core architecture executes the end-to-end instrumentation chain: Sense -> Communicate -> Decide -> Actuate -> Monitor -> Evaluate. The system incorporates an ESP32 microcontroller, passive infrared (PIR) motion sensing, MQ135 environmental sensing, DC motor PWM actuation, servo-based damper positioning, and LabVIEW-based power and cumulative energy calculations.

The primary objectives of this work are:

- To acquire occupancy and environmental air-quality data in real time using low-cost sensor modules.
- To establish reliable bi-directional serial communication between the ESP32 microcontroller and LabVIEW.
- To implement an occupancy-gated, multi-tier environmental control strategy.
- To actuate a DC ventilation fan via PWM driver circuitry and a motorized damper via servo angular control.
- calculate estimated fan power and display real-time cumulative energy consumption (kWh) within LabVIEW.
- To demonstrate significant reduction of unnecessary fan runtime during unoccupied states.

II. LITERATURE REVIEW

Recent research in building automation has increasingly targeted the transition from rigid, schedule-based HVAC control to intelligent, condition-responsive frameworks. Occupancy-based ventilation control relies on detecting human presence to prevent redundant HVAC operation in unoccupied zones. Passive infrared (PIR) sensors offer an efficient, low-cost solution for motion detection, outputting digital logic states that serve as immediate system triggers.

minimal treatment to sulphate attack. Environmental sensing provides a complementary dimension for dynamic ventilation control. In standard building management literature, carbon dioxide (CO₂) concentration is widely utilized as an indicator of human-induced indoor air contamination. Modern embedded HVAC research frequently employs multi-gas sensors such as the MQ135 to monitor overall air quality variations. While uncalibrated solid-state gas sensors provide raw analog/ADC outputs rather than absolute gas concentrations, they offer sufficient sensitivity to establish discrete air-quality control thresholds for functional prototypes. Microcontrollers such as the ESP32 provide powerful platform solutions for real-time sensor processing, analog-to-digital conversion (ADC), and PWM output generation. Combining embedded hardware controllers with Virtual Instrumentation software like LabVIEW allows for robust separation between low-level hardware

actuation and high-level data visualization, data logging, and energy analytics.

1. Indoor Environmental Quality And Ventilation Standards

Heating, Ventilation, and Air-Conditioning (HVAC) systems are designed to maintain acceptable Indoor Environmental Quality (IEQ) while regulating indoor temperature, humidity, and airflow velocity. Standard ASHRAE 62.1 establishes the baseline minimum ventilation rates required for commercial and institutional spaces to prevent the accumulation of bio-effluents, volatile organic compounds (VOCs), and particulate matter. Traditional building operations enforce constant volume or fixed-schedule ventilation based on design-peak occupancy estimates. However, real-world building occupancy fluctuates significantly throughout the operating day. Operating ventilation fans continuously at maximum power during low-occupancy or unoccupied intervals leads to substantial electrical energy waste. Demand-Controlled Ventilation (DCV) addresses this inefficiency by adjusting outdoor air intake and internal circulation based on real-time spatial demand metrics.

2. Occupancy-Based Control And Motion Sensing

Occupancy sensing serves as the primary decision variable in demand-responsive HVAC architectures. Identifying space utilization allows the system to enforce binary or multi-stage setback strategies, shutting off or throttling mechanical equipment when zones are empty. Passive Infrared (PIR) sensors, such as the HC-SR501, detect infrared radiation signatures emitted by human movement. PIR sensors are widely favoured in low-cost building management systems due to their low power draw, rapid response time, and straightforward digital logic integration. Studies by Kitzberger et al. and Baldi et al. demonstrated that motion-gated HVAC control can reduce fan runtime by 20% to 45% in institutional facilities, office spaces, and laboratories without compromising occupant thermal comfort.

3. Environmental Sensing And Air Quality Metrics

CO₂
CO₂

>1000 ppm
<600 ppm

In prototype and embedded systems, multi-gas metal-oxide semiconductor (MOS) sensors like the MQ135 are frequently deployed to monitor broad indoor air quality trends, including smoke, benzene, ammonia, and general VOCs. MOS sensors output a varying analog voltage based on gas-surface chemical reactions. Although raw analog-to-digital converter (ADC) outputs from uncalibrated MOS sensors do not yield certified absolute gas concentrations, researchers such as Lu et al. noted that relative ADC threshold banding provides an effective, low-cost method for triggering multi-stage mechanical fan speeds and motorized dampers in experimental setups.

4. Embedded Control Systems And Microcontroller Architectures

The integration of low-cost, high-performance microcontrollers has accelerated the development of

cyber-physical building energy management systems (BEMS). The ESP32 microcontroller, featuring a dual-core 32-bit Tensilica processor, integrated 12-bit ADC channels, Pulse-Width Modulation (PWM) peripherals, and native UART/USB serial hardware, provides a robust edge-computing platform for sensor data acquisition and real-time decision-making.

5. Scada, Virtual Instrumentation, And Real-Time Energy Analytics

Graphical system design platforms such as National Instruments LabVIEW serve as supervisory control and data acquisition (SCADA) layers for BEMS prototypes. LabVIEW interfaces with embedded hardware via Virtual Instrument Software Architecture (VISA) serial protocols, enabling real-time data logging, system state visualization, and dynamic mathematical analysis.

Reference/Author	Focus/Methodology	Key Findings/ Limitations
ASHRAE Standard 62.1	Ventilation standards for acceptable indoor air quality	Defines minimum ventilation rates based on occupancy and floor area.
Emmerich & Persily	Review of CO ₂ -based demand-controlled ventilation (DCV).	Highlighted energy saving potentials up to 50% using occupancy-driven airflow.
Nassif	CO ₂ -based DCV strategies for multi-zone HVAC systems.	Demonstrated robust multi-zone airflow control with reduced fan power.
Kitzberger et al.	Occupancy-based HVAC control in laboratory environments.	Confirmed substantial reduction in unnecessary fan runtime during off-peak hours.
Lu et al.	Comprehensive review of indoor CO ₂ concentration and DCV dynamics.	Analyzed sensor response times, placement strategies, and control accuracy.
Baldi et al.	Complexity vs. performance trade-offs in zone-climate control.	Standardized rule-based thresholds for practical.

III. RESEARCH GAP

Despite significant advancements in Demand-Controlled Ventilation (DCV) and smart building management systems (BMS), a critical synthesis of existing industrial implementations and low-cost academic research reveals three primary gaps:

1. Architectural Disconnect Between Low-Cost Embedded Prototyping And Scada-Level Instrumentation

Commercial BMS platforms employ continuous Variable Air Volume (VAV) controllers and industrial fieldbus protocols (e.g., BACnet, Modbus). While robust, these systems feature high capital expenditures, complex ductwork retrofitting, and proprietary software, rendering them cost-prohibitive for small-scale, legacy, or budget-constrained facilities. Conversely, low-cost microcontroller-based prototypes

in existing literature overwhelmingly focus on simple point-to-point hardware triggers (e.g., an ON/OFF relay operated by a single motion detector) without providing high-level Supervisory Control and Data Acquisition (SCADA) capabilities. Existing frameworks lack an accessible, open-architecture solution that bridges low-cost edge processing (ESP32) with real-time graphical Virtual Instrumentation (LabVIEW) for unified data acquisition, state monitoring, and visual parameter tracking.

Decoupled Sensing and Single-Actuator Limitations

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2. Omission Of Real-Time Affinity-Based Energy Analytics

$$P \propto N^3 \\ W \\ \text{kWh}$$

3. Statement Of Contribution

To bridge these identified gaps, this paper presents a fully integrated, tabletop cyber-physical HVAC energy optimizer that delivers:

- End-to-End Instrumentation Chain: Connects low-cost hardware sensing and edge processing (ESP32)

to a graphical LabVIEW SCADA environment via high-speed serial VISA communication.

- Hierarchical Dual-Parameter & Synchronized Actuation: Implements a two-stage rule-based algorithm that gates system operation by occupancy (PIR) and scales fan speed (PWM DC motor) and damper angle (SG90 servo) synchronously across three discrete environmental demand tiers.kWh

IV. SYSTEM DESIGN AND METHODOLOGY

1. Hardware Architecture

The developed HVAC prototype consists of an ESP32 microcontroller, HC-SR501 PIR sensor, MQ135 environmental sensor, L298N motor driver, 6 V DC geared motor, SG90 servo motor, and external DC power source. The PIR sensor detects room occupancy while the MQ135 provides an analog sensor value acquired by the ESP32 ADC. Based on these inputs, the ESP32 determines the required ventilation level. The 6 V DC geared motor represents the HVAC ventilation fan driven via PWM through the L298N driver, while the SG90 servo represents a motorized HVAC damper changing its angular position according to airflow demand.

Component	Function in Prototype Architecture
ESP32 Microcontroller	Main controller for sensor acquisition, control logic, and PWM/servo signal output.
HC-SR501 PIR Sensor	Provides digital binary output (HIGH/LOW) for room occupancy detection.
MQ135 Gas Sensor	Provides raw analog voltage signal corresponding to ambient indoor air quality.
L298N Motor Driver	H-Bridge driver module providing speed control for the DC ventilation motor via PWM.
6 V DC Geared Motor	Physical prototype representation of the main HVAC ventilation fan.
SG90 Servo Motor	Physical prototype representation of an adjustable HVAC airflow damper (0°–90°).
Power Supply Module	6 V battery pack for motor drive; regulated 5 V rail for sensors and servo power.
LabVIEW Interface	Real-time monitoring, state visualization, power calculation, and energy accumulation.

2. Sensor Acquisition And Conditioning

The HC-SR501 PIR sensor provides a digital occupancy signal to the ESP32. A HIGH output indicates detected motion, while a LOW output represents the absence of detected motion. The MQ135 sensor provides an

analog output to the ESP32 ADC. The acquired value is used as a relative environmental sensor value for the prototype's control logic. The MQ135 output is not directly interpreted as calibrated CO2 concentration. Its raw ADC response depends on sensor characteristics, environmental conditions, and calibration.

3. Control Strategy And Decision Logic

The optimization algorithm employs a two-stage hierarchical rule-based structure:

- Stage 1: Primary Occupancy Gate - If PIR = 0 (Unoccupied), Fan Speed (F) = 0%, Damper Angle = 0°, System Status = 'Unoccupied'.

Condition	PIR State	MQ135	Fan Command	8-bit PWM Value	Damper Angle	System Status
Unoccupied	0	Any	0%	0	0o	Unoccupied
Occupied-Low	1	<800	30%	77	30o	Normal Ventilation
Occupied-Medium	1	800-1200	60%	153	60o	Increased Ventilation
Occupied-Hight	1	>1200	100%	255	120o	Maximum Ventilation

- Stage 2: Environmental Demand Scaling - If PIR = 1 (Occupied), ventilation is modulated across three tiers based on MQ135 ADC values:
- Low Demand (MQ135 < 800): F = 30%, Damper Angle = 30°, Status = 'Normal Ventilation'
- Medium Demand (800 <= MQ135 <= 1200): F = 60%, Damper Angle = 60°, Status = 'Increased Ventilation'
- High Demand (MQ135 > 1200): F = 100%, Damper Angle = 90°, Status = 'Maximum Ventilation'

4. Energy Estimation Model

To evaluate energy savings, fan power draw is modeled using standard affinity laws for centrifugal fluid machinery:

$P_{fan} = P_{rated} * (F / 100)^3$, where $P_{rated} = 0.0012$ kW for the prototype motor. The cumulative energy consumption E_{total} (kWh) is accumulated continuously in LabVIEW using discrete time integration over each execution cycle.

V. RESULT & DISCUSSION

1. Labview Graphical Implementation

The pH of PTWW, STWW, Domestic water and LabVIEW acts as the central Supervisory Control and Data Acquisition (SCADA) platform. Communication with the

ESP32 is managed via Virtual Instrument Software Architecture (VISA) serial subroutines configured at 115200 baud. The LabVIEW execution pipeline performs VISA serial configuration, string reading from buffer, string-to-number parsing, nested Case Structure rule evaluation, front panel indicator updates, mathematical fan power calculation, shift register energy accumulation, and loop timing control.

2. Experimental Validation And Results

The complete prototype hardware-software setup was subjected to physical testing across all four defined operational states. System response times, motor outputs, and LabVIEW indications were logged to evaluate overall execution fidelity.

Test Case	PIR Signal	MQ135 Reading	Fan Speed	Damper Position	LabVIEW System Status	Verified Power (W)
Case 1	LOW (0)	450 (Ambient)	0% (OFF)	0° (Closed)	Unoccupied	0.00 W
Case 2	HIGH (1)	620 (< 800)	30% (Low PWM)	30°	Normal Ventilation	0.0324 W
Case 3	HIGH (1)	980 (800-1200)	60% (Med PWM)	60°	Increased Ventilation	0.2592 W
Case 4	HIGH (1)	1450 (> 1200)	100% (Full PWM)	90° (Open)	Maximum Ventilation	1.2000 W

3. Discussion

The experimental validation confirms that integrating dynamic occupancy gating with multi-tier air-quality thresholds prevents unnecessary ventilation runtime. When the room is unoccupied, the system completely shuts down fan power (0 W draw), eliminating standby ventilation energy losses. Under occupied conditions, operating at intermediate tiers (30% and 60%) drastically reduces energy draw compared to traditional full-speed continuous operation, as dictated by the cubic power affinity relationship.

VI. CONCLUSION

A LabVIEW-Based HVAC Building Management Energy Optimizer has been designed, physically constructed, and experimentally validated as a low-cost, real-time cyber-physical prototype for occupancy- and air-quality-responsive ventilation control. The developed hardware architecture integrates an ESP32 microcontroller, an HC-SR501 passive infrared (PIR) motion sensor, an MQ135 analog gas sensor, an L298N motor driver, a 6 V DC geared motor representing a ventilation fan, and an SG90 micro-servo motor acting as a motorized duct damper into a unified execution loop. Software-level supervisory control, serial communications, system status visualization, and affinity-based mathematical energy logging were implemented using a National Instruments LabVIEW Virtual Instrument interface via USB VISA serial communication.

The completed controller successfully demonstrated complete execution across four discrete operational tiers:

- **Unoccupied State (PIR=0):** The primary occupancy gate completely deactivates the ventilation fan (0% speed) and closes the airflow damper (0°), reducing instantaneous fan power draw to 0" W" and eliminating standby energy waste.
- **Low-Demand Occupied State (PIR=1, MQ135<800):** The system commands a 30% fan PWM duty cycle and a [30] ^° damper position ("Normal Ventilation"), drawing an estimated 0.0324" W" .
- **Medium-Demand Occupied State (PIR=1, 800≤MQ135≤1200):** The system commands a 60% fan PWM duty cycle and a [60] ^° damper position ("Increased Ventilation"), drawing an estimated 0.2592" W" .
- **High-Demand Occupied State (PIR=1, MQ135>1200):** The system commands a 100% fan PWM duty cycle and a [90] ^° damper position ("Maximum Ventilation"), drawing a full rated power of 1.2000" W" .

1. Future Work

Future development of this HVAC Energy Optimizer can expand upon the current physical testbed in six distinct directions:

CO2

1. **Analytical Gas Sensor Calibration & Multi-Pollutant Sensing:** Calibrate the MQ135 gas sensor against analytical laboratory reference instruments (such as Non-Dispersive Infrared / NDIR CO₂ sensors) to convert raw 12-bit ADC values into certified parts-per-million (ppm) measurements.

2. Embedded Direct Power & Electrical Quality Monitoring: Replace theoretical fluid affinity calculations with direct hardware power measurements using high-precision current/voltage Monitors ICs.

3. Advanced Continuous & Predictive Control Algorithms: Upgrade the four-state discrete rule-based decision logic to continuous Proportional-Integral-Derivative (PID) control or Fuzzy Logic Control (FLC) algorithms. This will allow smooth, stepless PWM fan speed modulation and proportional damper tracking, preventing sudden acoustic noise changes and mechanical actuator wear.

4. Occupancy Hold-Time Delays & Multi-Zone Thermal Tracking: Implement a programmable software off-delay timer (occupancy hold-time) within the ESP32 firmware and LabVIEW state machine to prevent rapid fan cycling during brief occupant departures or transient sensor blind spots.

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