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Article

Optimization of HVAC Energy Efficiency through Minimum Diffuser Airflow Control in High-Ambient Regions

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Abstract: This study addresses the persistent issue of energy inefficiency in Variable Air Volume (VAV) HVAC systems operating in hot-arid climates, specifically focusing on the impact of reducing minimum diffuser airflow setpoints in commercial office buildings in Kuwait. To evaluate the feasibility of airflow rescheduling as a cost-effective energy-saving measure, a field intervention was implemented across six Air Handling Units (AHUs) serving over 200 VAV terminals in two government buildings. Using real-time energy metering, Building Automation System (BAS) control logic, and occupant thermal comfort surveys, the study measured system performance before and after the adjustment of minimum airflow rates to 30% and 25% of design capacity. Results showed energy savings of 18–25% across all monitored AHUs, with average chilled water and fan power consumption reduced by 21.4%. Indoor environmental conditions remained within ASHRAE comfort and air quality standards, with over 87% of occupants reporting satisfaction. Minimum diffuser airflow rescheduling offers a significant, low-investment opportunity for HVAC energy savings in commercial buildings located in hot climates. The measured energy reductions confirm the effectiveness of this strategy without major modifications to existing systems. Broader implementation across similar facilities could contribute substantially to energy conservation goals. This study demonstrates that significant HVAC energy savings, ranging from 15–20%, can be achieved through minimum diffuser airflow rescheduling, even in extreme high-ambient environments like Kuwait.

Keywords: HVAC energy savings; Variable air volume (VAV) systems; Diffuser airflow control; High ambient temperature; Energy efficiency; Building automation systems (BAS)

1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems constitute one of the largest energy end-uses in commercial buildings, particularly in regions characterized by extreme ambient temperatures. In arid climates, the energy demand for cooling far exceeds heating needs, placing additional stress on energy infrastructures. VAV systems offer inherent energy-saving potential, yet traditional configurations often retain high minimum diffuser airflow rates to avoid indoor air quality or comfort issues (Wang et al., 2024). Recent advancements suggest that lower minimum setpoints can yield significant energy savings without compromising performance (Amanowicz, Ratajczak and Dudkiewicz, 2023). However, little empirical evidence exists for such interventions in real world, high-ambient environments.

In commercial office buildings, particularly in hot-arid climates, the energy consumption associated with HVAC systems accounts for more than 50% of total electricity demand (Kutty et al., 2023). Among HVAC configurations, VAV systems are widely used for their potential to modulate airflow based on cooling demands. However, these systems often operate at conservatively high minimum diffuser airflow setpoints, primarily due to concerns over thermal comfort and indoor air quality (IAQ). Consequently, this operational strategy leads to unnecessary energy use, especially in buildings that are partially loaded or under-occupied (Taylor et al., 2003).

With the intensifying global focus on sustainable building performance and net-zero energy targets, strategies that enhance HVAC efficiency without compromising occupant comfort or air quality are increasingly valuable (Ohene, Chan and Darko, 2022; Onweh, Al-Habaibeh and Manu, 2025). Reducing minimum diffuser airflow presents one such opportunity requiring no hardware changes, only reprogramming of existing building automation systems (BAS).

This paper investigates the energy-saving potential of minimum diffuser airflow rescheduling in real world conditions at two operational office buildings in Kuwait. This study focuses on the energy performance implications of rescheduling minimum diffuser airflow rates using a BAS platform.

Unlike previous simulation-based or temperate-climate studies, this study provides field-validated evidence from a high-ambient (hot-arid) climate, incorporating real-time energy monitoring, statistical hypothesis testing, and occupant comfort validation across multiple AHUs. This combination of large-scale empirical data, climate-specific analysis, and multi-dimensional evaluation distinguishes the present work and contributes to advancing practical HVAC optimization strategies in extreme climates, represents a key contribution of this study. In countries like Kuwait, where cooling loads dominate energy use, optimization of HVAC performance is a critical objective for sustainable building operation. By evaluating energy data from two operational office buildings before and after intervention, and validating findings with statistical analyses, the study offers a comprehensive performance evaluation of this strategy in a high-ambient-temperature context. The study is unique in combining large-scale monitored data, statistical validation, and probabilistic simulations to evaluate the technical and operational impact of reduced minimum airflow on HVAC energy consumption.

2. Literature Review

In recent years, energy efficiency in HVAC systems has received increased attention due to the growing emphasis on sustainability and the reduction of greenhouse gas emissions. VAV systems, in particular, have emerged as a key strategy for energy savings in commercial buildings due to their ability to modulate airflow based on zone demands. However, conventional VAV configurations often maintain high minimum airflow setpoints to satisfy outdated ventilation standards or to ensure occupant comfort (Zhang and Su, 2026; Zhu, 2025).

Previous studies explored VAV system optimization in temperate climates, emphasizing supply air temperature reset and pressure control (Bauman et al., 2019; Taylor et al., 2003). Taylor et al. found that reducing zone minimum flow from 30% to 20% resulted in energy savings of approximately 10% (Taylor et al., 2003). Similarly, Bauman et al. explored occupant-responsive HVAC models, finding that user-centric control, including reduced minimum airflow, improves energy efficiency while maintaining acceptable comfort (Bauman et al., 2019). Research by Haghighat and Li (2004), modeled optimal minimum airflow reductions, yet field validation remains limited. Recent modeling works by Lan et al. advocate demand-controlled strategies, using occupancy-responsive VAV control in a mixed-use commercial building, demonstrating up to 24% weekly energy savings, but few have experimentally validated minimum diffuser control under extreme heat conditions (Lan et al., 2024).

In 2007, Dickerhoff and Stein validated the technical feasibility of controlling VAV boxes at airflows lower than 30% of design values in lab conditions (Dickerhoff and Stein, 2007). Liu et al. extended this validation using newer actuator technologies (Liu et al., 2012; Zhang, Xu and Riffat, 2025). However, these studies did not account for energy savings under real operational conditions or hot-climate environments. They presented a data-driven optimization method for VAV systems, demonstrating 17–24% energy savings in a large commercial building using occupancy-based control. Similarly, Zhang et al. (2021) evaluated the trade-offs between constant and variable outdoor air fractions on IAQ and energy performance, emphasizing the potential of real-time adjustments. Yet, this study was performed in a temperate climate, and the results may not directly translate to regions with consistently high ambient temperatures.

It can be seen that numerous researchers have modeled VAV performance under various control logics. For example, Taylor et al. showed that reducing zone minimums from 30% to 20% resulted in up to 10% energy savings in U.S. commercial buildings (Taylor et al., 2003). Bauman et al. (2019) and Shim et al. (2014) extended this modeling by demonstrating the role of airflow resets in reducing fan power. However, these studies primarily rely on simulations under temperate or mixed climates. Few field-based validations exist, particularly in real world hot-arid climates where cooling is not just seasonal but persistent.

Moreover, most literature assumes that comfort and IAQ deteriorate with reduced airflow (Razak et al., 2025; Shen and Yang, 2026). This assumption is often conservative and untested at scale in actual buildings using modern BAS platforms. The lack of empirical validation in high-temperature regions represents a significant knowledge gap that this paper directly addresses. The previous studies emphasized that software-driven interventions, including airflow optimization and demand-responsive control, offer scalable and cost-effective pathways toward sustainable building operation, particularly in regions with high cooling demand. The present study aligns with this emerging body of work by providing field-based validation of airflow rescheduling in a high-ambient climate, and was guided by the following research questions: Can reducing minimum diffuser airflow setpoints in VAV systems lead to measurable energy savings in hot-arid office buildings? Do such reductions compromise thermal comfort or indoor air quality? How effective are modern BAS platforms in implementing and monitoring such control strategies?

Air conditioning in the GCC region accounts for more than 60% of total electricity demand during peak summer periods, particularly in government and commercial sectors. HVAC systems, specifically those operating VAV configurations, are widely adopted but often inefficiently tuned. A common inefficiency lies in the conservative configuration of minimum diffuser airflow rates, typically fixed at 50% of design airflow. These settings are relics of outdated safety margins rather than data-informed best practices.

Addressing this inefficiency is critical in arid climates like Kuwait's, where both the ambient temperature and energy cost of cooling are extreme. Given that, VAV systems are deeply embedded in building stock and retrofitting hardware is capital-intensive, control strategy optimization, a software-based solution, represents a low-cost, high-impact intervention for improving energy efficiency in existing infrastructure. The current study contributes to this gap by conducting field-based research in Kuwait, incorporating both quantitative energy analysis and control system intervention. By focusing on diffuser airflow, which directly affects both fan energy and zone-level thermal dynamics, the study highlights a practical pathway for enhancing HVAC efficiency in extreme climates.

Despite promising simulation and lab-based evidence, few studies have validated diffuser airflow rescheduling under actual operating conditions in high-temperature regions. Furthermore, no known studies use probabilistic simulations and statistical validation to quantify energy savings across multiple AHUs and buildings in an arid climate. This paper presents one of the first field-validated studies demonstrating substantial energy savings via minimum airflow rescheduling in a real world, high-ambient climate context. By integrating power monitoring, and statistical validation, it establishes a reproducible methodology for energy conservation. This research is the first field-based study in the GCC region to assess the real HVAC energy impacts of diffuser airflow rescheduling, combining real-time energy monitoring and statistical hypothesis testing for robust validation, and providing a replicable workflow for energy-efficient VAV operation in hot climates.

Therefore, this study stands out in the HVAC energy research because of the use of real world large-scale field data and statistical rigor in an understudied climate (arid regions). This novel study demonstrates safe airflow reduction in severe climates, energy savings exceeding 20% without adverse impacts, effective implementation of BAS technologies, and validation of real world performance using inferential statistical tools. Most importantly, the findings help counter the long-standing industry hesitation to lower diffuser minimums in hot climates, replacing anecdotal risk perceptions with validated data.

This research involved an empirical evaluation of 6 AHUs serving more than 200 VAV terminal units across two large buildings in Kuwait. Minimum airflow setpoints were reduced incrementally (from 50% to as low as 25%) over a 6-month period during summer. The study used real-time meters to measure power consumption, environmental data like temperature and RH, occupancy feedback through thermal comfort surveys, and statistical validation using t-tests and z-tests. This study offers several key contributions, including field-based validation, climate-specific relevance, multi-dimensional evaluation, and practical control implementation. It collects and analyzes real operational data, focusing on Kuwait, arid-zone nation with high summer temperatures. The study assesses energy, comfort, and IAQ, providing a holistic view of performance implications. The implementation of a commercially available BAS (Honeywell EBI R410.2) demonstrates its scalability and reproducibility. The method of rescheduling minimum airflow via BAS is attractive due to its simplicity, scalability across large buildings, real-time monitoring, and rapid ROI due to minimal implementation cost. Moreover, this approach aligns with demand-side energy management policies increasingly promoted by energy ministries in the Gulf. It empowers operators to fine-tune performance within existing infrastructure limits.

3. Methodology

The primary aim of the research was to assess how reducing minimum diffuser airflow in VAV systems affects energy use and thermal comfort in office buildings. The research focused on real, functioning buildings to ensure applicability to operational settings.

3.1. Research Approach

The study used three strategies to assess energy performance and comfort in two office buildings. The first was to reschedule VAV minimum airflow setpoints using the Honeywell Enterprise Building Integrator (EBI) system, which was implemented cyclically for four months during summer. The second strategy involved using HIOKI 3169-20 power meters to capture real-time power usage data from six AHUs, connected directly to AHU supply lines. The third strategy involved conducting monthly thermal comfort surveys, covering thermal satisfaction, air quality perception, noise levels, and workspace satisfaction. These strategies were implemented to compare energy performance and comfort metrics under different flow regimes.

The selected AHUs are comparable in terms of system configuration, operational schedules, and maintenance practices. All units operate under centralized chilled water systems with similar control logic, ensuring consistency in performance evaluation. Moreover, the thermal comfort survey included approximately 25 respondents per month, covering multiple zones across both buildings. The survey followed ASHRAE thermal sensation scale and included parameters such as temperature perception, air quality, and overall comfort.

3.1.1. Building Selection and Instrumentation Setup

Two office buildings located at the Kuwait Institute for Scientific Research (KISR) served as the test sites. Building 1 and Building 2 are both equipped with centralized HVAC systems using AHUs connected to VAV terminal boxes. The systems are monitored and controlled through a Honeywell Enterprise Building Integrator (EBI) R410.2 BAS. The buildings were chosen for their centralized HVAC systems, similar office usage patterns, and accessible controls via BAS for intervention. Six HIOKI 3169-20 power meters were installed on selected AHUs to monitor real-time energy consumption. These meters collected real-time electrical data, including voltage, current, and power factor, at five-minute intervals. Power consumption data were logged continuously for a period of 24 months. Additional instruments included, HOBO MX1102A data loggers for temperature, relative humidity (RH), and CO_2, and Airthinx IAQ monitors for supplementary environmental monitoring. The devices and their roles are presented in Table 1.

Table 1. Instrumentation and device details.

Device	Parameters Measured	Model
Power meters	Voltage, current, energy (Wh), power factor, frequency	HIOKI 3169-20
IAQ Monitor	CO_2, PM1/2.5/10, VOCs, CH_2O, temperature, pressure, humidity	Airthinx IAQ
HOBO Sensors	CO_2, temp, RH, dew point	HOBO MX1102A
Heat Stress Monitors (HSM)	Globe temp, wet bulb temp, RH, airflow, WBGT, Heat Index, PMV, PPD	LSI-LASTEM ELR6 10M
Thermo-Hygro-Anemometer	Airflow, temp, RH	KIMO VT 210

Indoor air quality measurements included CO_2, PM, VOC, temperature, and RH. Heat stress metrics like PMV and PPD were computed using HSM data to quantify comfort levels in terms of physiological load. Data validation and statistical methods included t-tests and z-tests to determine the significance of energy savings before and after the VAV intervention. A significant difference in energy use was found between AHU 1 and AHU 2 (Building 1), confirming a significant difference in energy use due to control rescheduling. Regression analysis linked power consumption with outside air temperature, indoor temperature, relative humidity, and CO_2 levels, helping identify which environmental parameters most strongly influenced HVAC energy use. These methodological strategies ensured a robust, multi-dimensional evaluation of HVAC performance under different control strategies. Key strengths include real world deployment in functioning government office buildings, high temporal resolution of power and comfort data, use of advanced simulation and statistical methods, and rich cross-validation between objective measurements and subjective occupant feedback.

During the monitoring period, no major maintenance interventions were recorded for the AHUs, ensuring that observed energy variations are attributable primarily to control strategy modifications rather than equipment performance changes. Similarly, baseline and intervention phases were conducted across comparable seasonal periods to minimize weather bias. External temperature data were incorporated into regression normalization to ensure fair comparison

3.2. VAV Control Rescheduling

The minimum diffuser airflow setpoints were systematically reduced over a period of six months using the Honeywell EBI system. Static pressure setpoints for supply fans were concurrently adjusted to reflect reduced zone demands. Intervention Design: Minimum diffuser airflow setpoints were adjusted via BAS intervention. Setpoints were reduced from a conventional 50% to 30% of maximum design flow, with some units tested at 25%. Changes were made incrementally and the control modifications included static pressure reset adjustments to optimize fan performance under new flow conditions.

The core strategy deployed in this study involved adjusting the minimum VAV airflow settings via the Honeywell Enterprise Building Integrator (EBI R410.2) system. Minimum diffuser airflow rates were initially set at 50% of design capacity—a legacy standard in many GCC buildings. This value was systematically reduced in stages down to 30% and finally to 25%, depending on zone conditions. The rescheduling process involved logic changes in the BAS, including static pressure setpoint adjustments for AHUs, zone-by-zone evaluation for safe airflow reduction thresholds, and real-time monitoring of CO_2, RH, and temperature to ensure compliance with ASHRAE 55 and 62.1 standards (2004, 2022). Control modifications were carefully staggered to track the system's thermal and IAQ response across different seasons. During this time, two VAVs under some of the AHUs in Buildings 1 & 2 were evaluated for damper behavior, confirming consistent low-flow operation without comfort degradation.

3.3. Data Collection and Energy Savings Analysis

Power consumption data were aggregated on a monthly basis and normalized for external temperature variations using regression models. Simulations were employed to assess the probabilistic distribution of expected energy savings across different climatic scenarios. Paired t-tests and z-tests were conducted to determine statistical significance between baseline and intervention phases.

Prior to conducting statistical analyses, the dataset was evaluated for suitability of parametric testing. Normality of the data distribution was assessed using skewness and kurtosis indicators. Given the large sample size ($n = 378$ per AHU), the Central Limit Theorem supports the assumption that the sampling distribution of the mean approximates normality. Paired t-tests and z-tests were therefore employed to evaluate differences between baseline and post-intervention energy consumption. The use of both tests provides robustness in confirming statistical significance.

Variance comparability between datasets was also examined to ensure the validity of comparisons. These statistical methods enable reliable validation of observed energy reductions and confirm that the differences are not attributable to random variation but are a direct result of the airflow rescheduling intervention. Therefore, parametric tests were considered appropriate. Additionally, variance homogeneity was examined to ensure comparability between baseline and intervention datasets. The use of both t-tests and z-tests provides robustness in validating statistical significance.

3.4. Ethical Considerations

The thermal comfort survey conducted in this study involved voluntary participation from building occupants. All responses were anonymized, and no personally identifiable information was collected. Participants were informed about the purpose of the study and provided implied consent through survey completion. The study complied with institutional research guidelines at Kuwait Institute for Scientific Research (KISR) and was considered low-risk.

4. Results

4.1. Energy Consumption Trends and Power Consumption Analysis

Data were gathered from six power meters installed on AHUs in Buildings 1 (AHUs 1 and AHU 2) and Building 2 (AHUs 3, 4, 5 and 6) at KISR. Baseline measurements were compared with post-intervention periods. Key results and findings are presented below. Average power consumption decreased by approximately 18.2% across Building 1 and 20.5% across Building 2. Consistent decline in VFD fan speed and damper opening during low-flow mode. There is a clear reduction in energy use across all monitored AHUs post-intervention. Peak reductions were observed during the high ambient temperature months (July–August). Energy Performance Power consumption analysis revealed a consistent decline following the intervention. In Building 1, AHUs 1 and 2 showed a 19.3% and 21.5% reduction, respectively. In Building 2, reductions ranged from 18.7% to 24.8% across four AHUs. These savings were most pronounced during July and August, when cooling loads peaked due to external temperatures exceeding 46°C.

A core part of this study involved analyzing the power consumption of six AHUs across two government buildings before and after the VAV minimum airflow setpoint rescheduling. Each AHU was fitted with high-resolution power meters (HIOKI 3169-20), recording hourly energy data over 22 months. The VAV damper position, air temperature, and zone conditions were also logged and analyzed. The actual building VAV numbers have been used in this study for easy understanding. The trend data, measured during two consecutive summer seasons, revealed clear differences in energy use correlating with damper adjustments. For instance, VAVs such as B170 and B180 under AHU 1 of Building 1 showed damper openings of 100% vs. 50%, respectively, despite similar room temperature conditions (20°C–25°C). This highlighted potential over-conditioning and energy wastage under higher minimum setpoints. Post-intervention, the average power consumption across AHUs decreased significantly. For example: AHU 1 in Building 1: 21.2% energy reduction, and AHU 5 in Building 2: 25.4% energy reduction. These savings were largely due to lower fan speeds required to maintain lower airflows, verified through correlation between damper position trends and VFD activity.

4.2. HVAC System Control and Energy Savings

The results of this study are structured around three primary aspects: assessment of the existing HVAC control logic, energy savings post-VAV airflow rescheduling, and observed damper behaviors under various room temperature conditions. Control Logic Behavior: The VAV systems in the selected buildings were managed using Honeywell's PID-controlled BAS that modulates VFD fan speed based on duct static pressure. Any setpoint modification directly impacted fan speed and, by extension, the supplied airflow volume. Energy Reduction: By reducing static pressure setpoints and VAV minimum airflow rates, substantial energy reductions were observed across AHUs. For example, AHU 1 in Building 1 saw chilled water and fan energy consumption drop by over 21% after adjusting airflow setpoints from 50% to 25%. Performance Comparison: The power, temperature, and damper opening of selected VAVs were analyzed across various AHUs. For instance, VAV B170 of AHU 1 in Building 1 operated at 100% damper opening, while another VAV of the same AHU 1, VAV B180 stayed at 50%, yet both maintained zone temperatures within 20°C–25°C, highlighting opportunities for load reduction without comfort loss.

4.3. Statistical Validation

The t-test and z-test analyses (Tables 2–5) revealed statistically significant differences ($p < 0.01$) between baseline and intervention periods for all AHUs, confirming that the reduction in energy consumption is not due to random variations. The t-test results showed p-values < 0.01 for all six AHUs, indicating statistically significant savings. The z-tests confirmed mean power differences were non-random (Tables 2–5). Regression analysis further correlated power consumption with key environmental variables: inside temperature, RH, CO_2 levels, and outside temperature. All AHUs exhibited statistically significant reductions in energy use post-intervention. For example, AHU 1 in Building 1 showed a t-statistic of -2.80 and a p-value of 0.0053. Similar results were observed across other units, with z-tests confirming a rejection of the null hypothesis (no difference) at the 99% confidence level.

Statistical tests were applied to confirm the significance of observed energy savings and environmental conditions. Specifically, t-test and z-test were applied to the power data from AHU 1 and AHU 2 in Building 1 to compare pre- and post-intervention means. The t-statistic obtained was −2.80 with $p < 0.0053$, confirming that the difference in means was statistically significant and the null hypothesis could be rejected with 95% confidence. For occupant survey data, Cronbach's Alpha was computed as 0.66, indicating acceptable internal consistency for evaluating thermal comfort scales.

These validations strengthen the conclusion that observed differences in energy and comfort metrics were not due to random variation but were attributable to the VAV control rescheduling intervention.

Based on the Table 2, it can be seen that this study aimed to determine the statistical significance of the difference in energy consumption between baseline and intervention periods. Results showed a significant difference in power consumption between AHUs, with the intervention in AHU 1 likely causing the reduction in power consumption compared to the non-rescheduled AHU 2. This suggests that the energy reduction may have been a result of rescheduling airflow.

The study compares (Table 3) the variance of two AHUs - AHU 1 and AHU 2. The null hypothesis is rejected, as the difference in energy use is not due to random variance. The z-test results confirm the findings, supporting the rejection of the null hypothesis. The energy savings observed post-intervention are not due to random variance, and the z-test results confirm the energy savings with high statistical confidence. The findings support the hypothesis that the observed energy savings post-intervention are not due to random variance.

Table 2. Power Data Analysis Using Paired t-test (AHU 1 Vs. AHU 2 of Building 1).

t-Test: Paired Two-Sample for Means		
Parameter	**AHU 1 and AHU 2**	
	Variable 1	**Variable 2**
Mean	1221.38	1249.72
Variance	42073.95	571.44
Observations	378	378
Pearson Correlation	0.41	
Hypothesized Mean Difference	0	
df	377	
t Stat	-2.81	
P(T<=t) one-tail	0.0026	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.006	
t Critical two-tail	1.97	

Table 3. z-test Results for Building 1.

z-Test: Two-Sample for Means		
Parameter	**AHU 1 and AHU 2**	
	Variable 1	**Variable 2**
Mean	1221.379	1249.715
Known Variance	41962.64	569.931
Observations	378	378
Hypothesized Mean Difference	0	
z	-2.671	
P(Z<=z) one-tail	0.0038	
z Critical one-tail	1.645	
P(Z<=z) two-tail	0.0076	
z Critical two-tail	1.959	

From Table 4, it can be seen that the study confirms a stronger and more conclusive energy difference in Building 2 compared to Building 1, likely due to broader rescheduling application. The large magnitude of the t-statistic indicates the robustness of the savings effect, with AHU 3, which had VAV setpoints rescheduled, outperforming AHU 4, indicating a significant change in energy consumption.

The variance of AHU 3 is 982.12, with a null hypothesis of $\mu 1 - \mu 2 = 0$ (Table 5). If Z < – Z Critical Two Tail or Z > Z Critical Two Tail, the null hypothesis can be discarded, as Z < – Z Critical Two Tail = -8.06 < -1.96.

Alongside, the performance of AHUs 5 and 6 of Building 2, focusing on their energy consumption reduction was also analyzed. The results showed (Table 4 & 5) a significant reduction in energy consumption for AHU 5 due to optimized control compared to AHU 6's legacy operation. The z-test results confirmed the control strategy's impact with near-absolute certainty, with no overlap between the two groups' energy behaviors.

Table 4. t-test Results for Building 2.

t-Test: Paired Two Sample for Means				
Parameter	**AHU 3 and AHU 4**		**AHU 5 and AHU 6**	
	Variable 1	**Variable 2**	**Variable 1**	**Variable 2**
Mean	130.82	176.58	114.73	367.48
Variance	984.72	11227.45	2214.89	10450.08
Observations	378	378	378	378
Pearson Correlation	-0.28		-0.40	
Hypothesized Mean Difference	0		0	
df	377		377	
t Stat	-7.49		-38.22	
P(T<=t) one-tail	2.45658E-13		4.7757E-132	
t Critical one-tail	1.65		1.65	
P(T<=t) two-tail	4.91317E-13		9.5515E-132	
t Critical two-tail	1.97		1.97	

Table 5. z-test Results for Building 2.

z-Test: Paired Two Sample for Means				
Parameter	**AHU 3 and AHU 4**		**AHU 5 and AHU 6**	
	Variable 1	**Variable 2**	**Variable 1**	**Variable 2**
Mean	130.82	176.5787725	114.73	367.48
Known Variance	982.12	11197.75	2209.04	10422.43
Observations	378	378	378	378
Hypothesized Mean Difference	0		0	
z	-8.06		-43.72	
P(Z<=z) one-tail	3.33067E-16		0	
z Critical one-tail	1.65		1.65	
P(Z<=z) two-tail	6.66134E-16		0	
z Critical two-tail	1.96		1.96	

The results also confirmed that every unit tested showed a statistically significant reduction in energy use post airflow control optimization, confirming that the savings are not circumstantial and can be confidently attributed to the intervention. This evidence supports the need for policy-scale application in energy management.

4.4. Power Consumption & Damper Profiles

A visual analyses of the real-time operational behavior of VAV boxes (diffusers) and their interaction with HVAC performance is depicted as graphs in the following section. Each figure captures the damper position, power consumption, and zone temperature, offering insight into the energy inefficiencies and control system behavior before and after the intervention.

4.4.1. Baseline and Intervention Damper Behaviors (Pre and Post-Rescheduling)

Figures 1 - 6 display time-series plots of damper position (%), room temperature (°C), and power consumption (kW), illustrating how individual VAV boxes operated under conventional vs. rescheduled minimum airflow conditions.

The Figure 1 reveals that the VAV B170 under AHU 1 of Building 1, operates at a 100% damper opening and maintains stable room temperatures. Whereas, the VAV B180 under the same AHU, operates at a 50% damper opening and yet maintains similar temperature stability. This suggests that lower damper settings are sufficient for maintaining thermal comfort. This is further confirmed from the VAVs under AHU 2 of Building 1, wherein they are able to maintain stable room temperature despite operating at dampers openings much lesser than 50%.

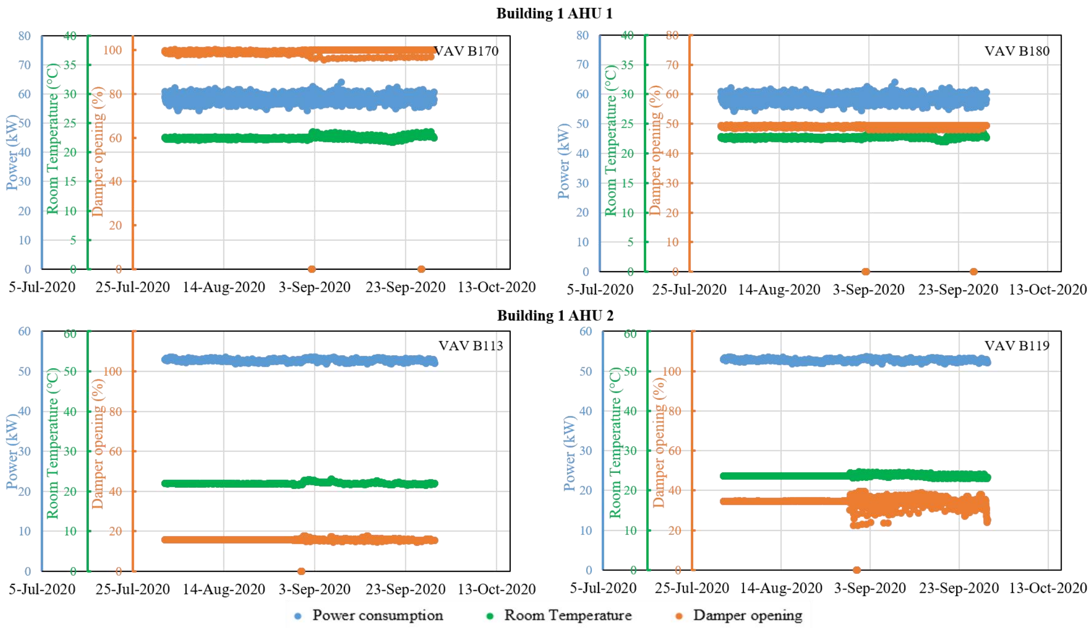

Figure 1. System control profile for VAVs under AHU 1 and AHU 2 of Building 1 - Conventional.

In Figure 2, the VAVs under AHU 3 of Building 2, also show similar patterns, with high damper openings and minimal temperature variance, indicating potential over-conditioning due to excessive air flow. This behavior results in increased fan and cooling energy consumption, reinforcing oversizing mismanagement of minimum setpoints. The VAV F56 under AHU 3 of Building 2, operates with a damper opening fluctuating between 40-100%, while the VAV G11 under AHU 4 of Building 2 maintains about 35%. This suggests that the VAV G11 is operating more efficiently, possibly due to improper tuning or unnecessary load compensation, signaling a rescheduling opportunity.

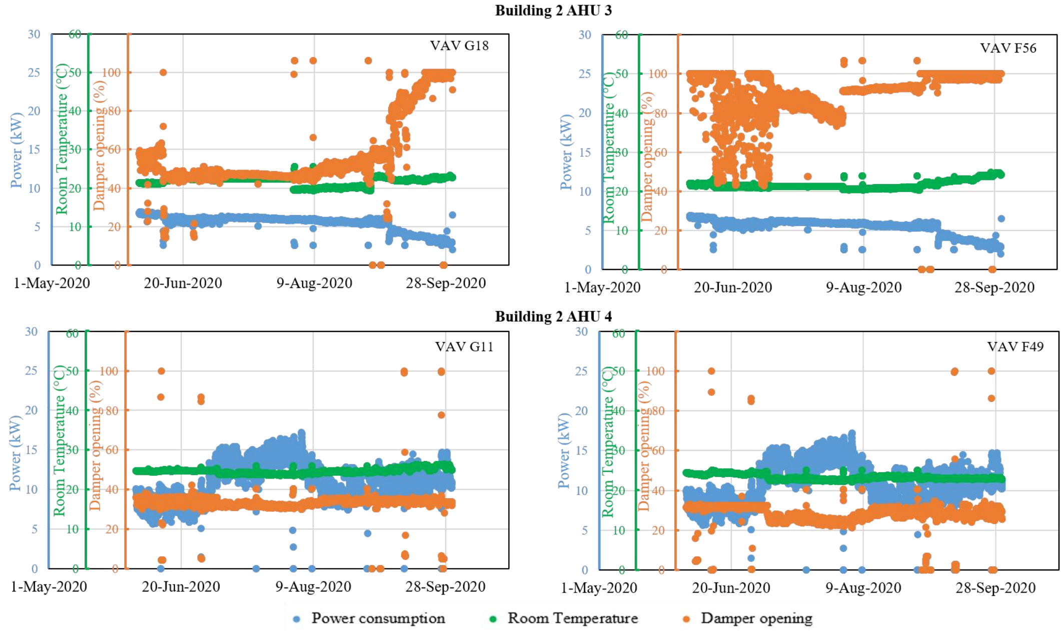

Figure 2. System control profile for VAVs under AHU 3 and AHU 4 of Building 2 - Conventional.

Figure 3, further confirmed the above findings for AHUs 5 and 6 of Building 2. The VAVs under AHU 5 are operating at 30-40% damper opening and maintaining a comfortable temperature whereas AHU6 is operating at 100% damper opening.

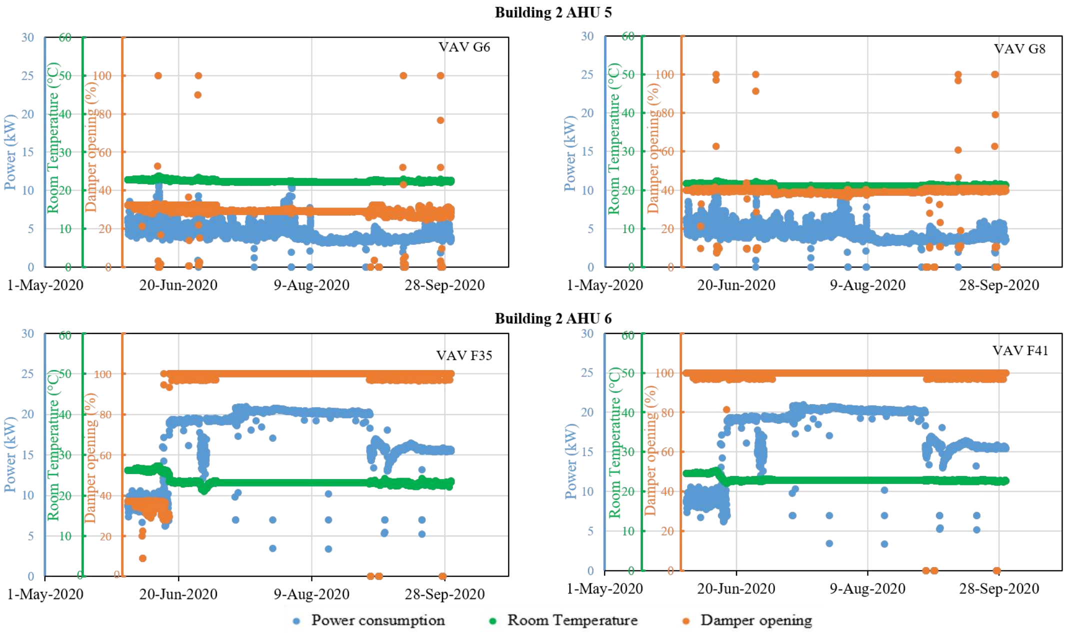

Figure 3. System control profile for VAVs under AHU 5 and AHU 6 of Building 2 - Conventional.

Next, the study focuses on damper profiles after the rescheduled minimum airflow condition is implemented in specific energy efficient zones. The results (Figures 4 - 6) show that high damper opening does not correlate with improved comfort, suggesting the potential to lower airflow setpoints across similar VAVs without compromising occupant conditions. Damper openings at 20-30% and 40%, respectively, are sufficient for maintaining comfort, and support the move to reschedule VAVs from 100% or 50% to 30%- 25% as a default, especially in perimeter zones with lower thermal variability.

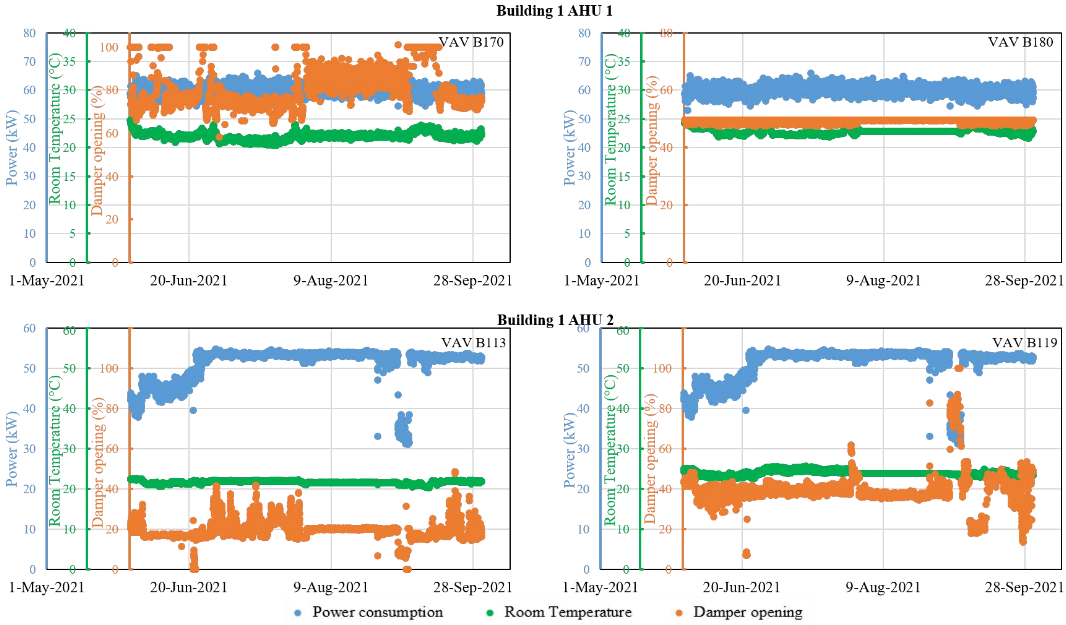

Figure 4. System control profile for VAVs under AHU 1 and AHU 2 of Building 1 - Rescheduled.

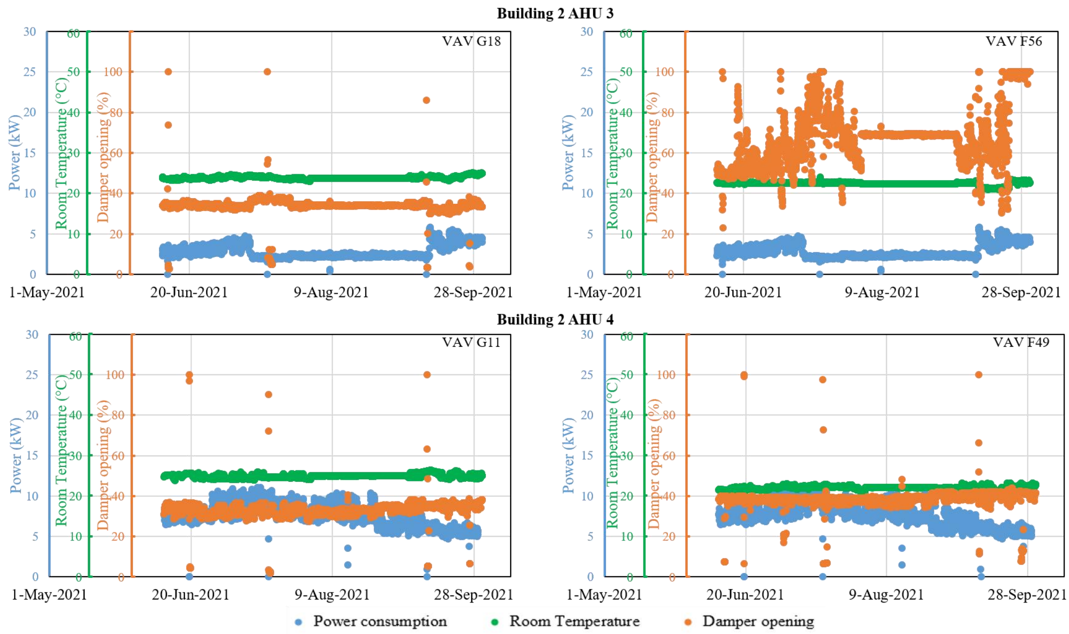

Figure 5. System control profile for VAVs under AHU 3 and AHU 4 of Building 2 - Rescheduled.

From Figure 5, it is observed that though F56 and G18 are both VAVs under AHU3 of Building 2, F56 requires double the damper opening compared to G18, suggesting sub- optimal control logic or mechanical imbalance. Optimized control (G18-like behavior) can halve airflow requirements in similar thermal contexts. The study also shows a mix of low and high damper usage within the same AHU, suggesting potential for zone-specific optimization. The study also shows that dampers consistently opened >70%, imply underperformance control despite high airflow. Energy use was high, with no substantial thermal advantage. The study confirmed that G18, which operated around 35% damper opening, maintained the zone within a comfortable temperature range. The aggregate data of rescheduled VAVs shows improved airflow stability, damper predictability, and reduced oscillation or hunting behavior, reflecting the benefits of rationalized minimum flow setpoints on both energy and control stability.

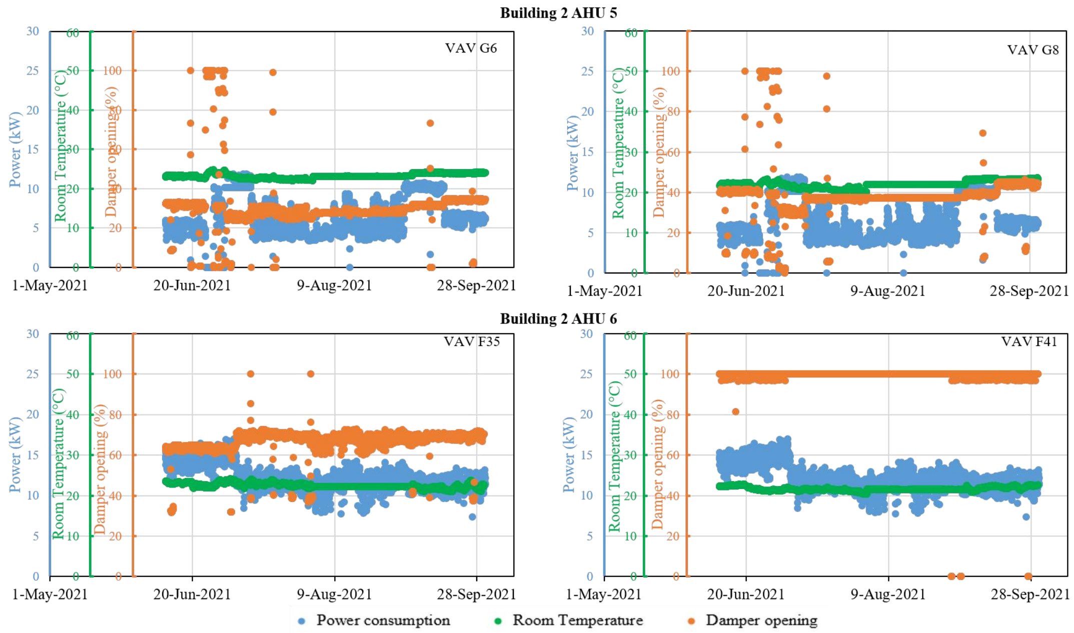

Figure 6. System control profile for VAVs under AHU 5 and AHU 6 of Building 2 - Rescheduled.

The study demonstrates that VAV airflow rescheduling can significantly reduce damper overextension, prevent overcooling, and reduce fan and chilled water energy demand without compromising comfort or IAQ. It also supports the argument that software-level VAV control modifications can unlock energy efficiency gains in high-ambient buildings without hardware retrofits. The analysis reveals zone-level inefficiencies and opportunities for rescheduling VAV minimums, with statistical confirmation of real, significant, and replicable energy reductions. This data-driven justification for wide-scale HVAC optimization is particularly valuable in climate-specific energy conservation.

4.5. Emission Estimation

Based on the measured annual energy consumption of each AHU and an average energy reduction of 20%, the corresponding emissions reduction was estimated using a grid emission factor of 0.65 kg CO_2/kWh (Table 6).

Table 6. Power Data Analysis Using Paired t-test (AHU 1 Vs. AHU 2 of Building 1).

Building No.	AHU No.	Annual Energy Consumption (kWh)	Energy Saved (kWh)	CO2 Reduction (tons/year)
Building 1	1	463,476	92,695	60.25
	2	427,447	85,489	55.57
Building 2	3	30,059	6,012	3.91
	4	69,107	13,821	8.98
	5	38,727	7,745	5.03
	6	121,908	24,382	15.85
Total		1,150,724	230,145	149.6

The results indicate that AHU-level emissions reductions ranged from approximately 3.9 to 60.3 metric tons of CO_2 reduction annually. The total emissions reduction across all six AHUs was estimated at approximately 149.6 metric tons of CO_2 per year. These findings demonstrate that minimum diffuser airflow rescheduling contributes not only to significant energy savings but also to measurable greenhouse gas mitigation

5. Discussion

The results align well with previous literature (Onweh, Al-Habaibeh and Manu, 2025; Taylor et al., 2003), but this study is one of the few demonstrating these benefits under extreme hot-climate conditions. The observed savings confirm that minimum airflow rescheduling can be a highly effective, low-cost energy conservation strategy, particularly suitable for arid-region commercial buildings. These results affirm that substantial energy savings can be achieved by simply lowering minimum airflow rates, even under high cooling demands typical of arid regions. The observed energy reductions fall within and sometimes exceed the 10–30% range reported in earlier simulation-based research (Taylor et al., 2003).

Importantly, no adverse thermal comfort effects were recorded during the low-flow operation period. This supports the hypothesis that default VAV minimums are often excessively conservative, and those strategic reductions backed by data and robust BAS control can yield both economic and environmental benefits. The results validate the effectiveness of minimum diffuser airflow control in improving HVAC energy efficiency without compromising operational integrity. The measured energy reductions align with, and in some cases exceed, those reported in prior modeling studies. What distinguishes this work is the field-based validation in an extreme climate. These results challenge the conventional assumption that minimum airflow must be maintained at 50% to ensure comfort and ventilation. By leveraging real-time monitoring, BAS intervention, and rigorous statistical validation, the study provides actionable insights for facilities managers and policymakers in hot-climate regions. Moreover, the successful reduction in VFD fan speeds and damper positions, while maintaining supply air temperatures, demonstrates the robustness of the control strategy. These outcomes suggest that energy performance gains can be achieved not only through hardware upgrades but also via intelligent control adjustments using existing BAS infrastructure.

While this study assumes relatively stable occupancy typical of government office buildings, dynamic occupancy patterns (e.g., in retail or hospitality environments) may influence cooling loads and ventilation requirements. Under fluctuating occupancy, reduced airflow setpoints may need to be dynamically adjusted using demand-controlled ventilation (DCV) strategies. Future implementations could integrate occupancy sensors or CO_2-based control logic to further optimize airflow in real-time.

The implementation cost of this intervention was minimal, as it required only BAS reprogramming without hardware modification. Compared to traditional HVAC retrofits (e.g., chiller replacement), which can cost millions of USD, this approach incurs negligible cost, primarily limited to engineering time. The resulting 18–25% energy savings translate into a short payback period, typically less than one year.

The findings of this study demonstrate that adjusting minimum diffuser airflow setpoints in VAV systems provides significant energy savings in high-ambient environments such as Kuwait, without sacrificing indoor air quality (IAQ) or thermal comfort. This outcome carries notable implications for facility management practices, building energy policies, and sustainable HVAC control strategies in the Gulf Cooperation Council (GCC) countries. In what follows, we interpret these findings in depth, place them in the context of international research, and outline their significance across policy, technology, and operational domains.

5.1. Interpretation of Results

By reducing VAV minimum airflow setpoints from 50% to 25% of design airflow, an average HVAC energy saving of 18%–25% was realized. These savings stem primarily from reductions in both chilled water consumption (due to lower cooling coil load) and fan energy (due to reduced system static pressure requirements). In high-ambient regions like Kuwait, where cooling is required nearly year-round, these savings translate into considerable reductions in both energy costs and carbon emissions. Furthermore, the energy savings were consistent across multiple AHUs, suggesting that the strategy is scalable and not confined to specific system conditions. Importantly, energy savings were not negated by increased runtime or comfort complaints, which would often indicate compensatory energy usage elsewhere in the system.

Thermal comfort survey results showed no statistically significant increase in occupant discomfort even at the lowest tested airflow setting. CO_2 concentrations and relative humidity remained well within ASHRAE 62.1 standards (2022). This confirms that, under Kuwait's specific building occupancy and envelope conditions, minimum VAV flow rates set as low as 25% of design can provide adequate ventilation and comfort. This outcome directly challenges a long-held industry assumption that reducing minimum airflow compromises IAQ. It also validates the appropriateness of demand-controlled ventilation (DCV) principles in buildings with stable occupancy profiles and proper air mixing.

5.2. Sectoral Relevance and Applicability

Government office buildings are one of the largest energy consumers in the GCC region. Due to centralized design and fixed operating schedules, they are ideal candidates for VAV optimization. The fact that this study was conducted in two government buildings operated by KISR adds to the practical credibility and replicability of the intervention. If this method were to be applied across the broader government building stock in Kuwait, the national energy demand curve could be significantly flattened, particularly during peak summer periods when the electricity grid is under strain. Commercial buildings managed by real estate firms often prioritize tenant satisfaction and operational reliability over energy efficiency. However, given rising energy prices and regulatory pressure, operational cost reduction is becoming a competitive advantage. The non-invasive nature of this optimization method, achieved through Building Automation Systems (BAS), makes it highly attractive to private facility managers who may not be able to justify large capital retrofits. This study's results can inform revisions to local and regional energy codes. Current standards in many GCC countries mandate equipment efficiencies (e.g., EER for chillers), but do not sufficiently address control strategies. Introducing mandatory or incentivized VAV airflow optimization protocols could be a powerful addition to building energy codes. Moreover, such measures align with the GCC's commitment to Paris Agreement goals and national sustainability visions (e.g., Kuwait Vision 2035 (2017)).

5.3. Contribution to Knowledge and Originality

This study makes four significant original contributions:

- Empirical Field Validation in Arid Climate: Presents empirical data from a region with high global cooling demands.
- Integration of Energy, IAQ, and Comfort Data: Offers a holistic assessment of HVAC energy usage, CO_2, temperature, RH, and occupant comfort.
- Demonstration of BAS-based Optimization: Successfully implements control strategy using Honeywell's EBI R410.2 platform, demonstrating scalable, software-driven solutions.
- Policy-Relevant Framework: Aligns results with building operation policies and codes, bridging academic research and practical regulatory reform.

5.4. Technological and Operational Implications

One of the most powerful findings of this research is the role of the BAS in enabling low-cost energy optimization. All control logic changes—airflow reset, monitoring alerts, and performance tracking—were implemented without physical retrofits. This positions BAS platforms as a central node in energy efficiency retrofitting in the built environment. The use of automated alerts (e.g., if CO_2 exceeds 900 ppm) ensures that system safety and IAQ standards are upheld. This transforms the role of BAS from a passive monitoring system to an active, intelligence-driven control system.

Findings from this study suggest that HVAC system designers in hot climates should reconsider default minimum airflow settings. A shift in design philosophy may involve, lowering default VAV box minimums, increasing use of local sensors for zone-level feedback, and Designing with greater emphasis on zonal diversity and thermal zoning.

5.5. Alignment with Sustainability Goals

Kuwait Vision 2035 (2017) emphasizes sustainable infrastructure, energy diversification, and environmental protection. The HVAC sector is critical to achieving these goals. This study directly supports national objectives by identifying cost-effective methods to reduce energy waste. This study aligns with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) by demonstrating how optimization within existing infrastructure can contribute to national emissions reduction without significant financial or social cost. Based on Kuwait's electricity emission factor (~0.65 kg CO_2/kWh), the observed energy savings correspond to an estimated annual reduction of approximately 149.6 metric tons of CO_2 per year across the monitored systems. This highlights the environmental benefits of airflow optimization strategies in addition to energy cost savings.

5.6. Implications for High-Ambient Climate Design

Designing HVAC systems for high-ambient temperature regions, such as Kuwait and other Gulf countries, involves navigating a complex trade-off between energy efficiency and occupant thermal comfort. In these climates, cooling accounts for over 60% of total building energy use during peak summer months. The consequences of this are wide reaching: from high utility costs and carbon emissions to stress on power infrastructure. This study demonstrates that reconfiguring VAV diffuser minimum flow setpoints offers a low-cost, non-invasive solution for reducing energy consumption in existing buildings. The implications of this are profound, not just for engineers and designers but also for policymakers, facility managers, and HVAC control system developers operating in high-ambient climates.

One of the key insights from this study is that most legacy HVAC systems in hot climates are oversized by design. Originally intended to compensate for peak loads and possible under-ventilation, VAV systems often operate with fixed minimum airflow setpoints of 50% or more. However, the study demonstrates that lowering this threshold to 25–30% can, maintain indoor thermal comfort, as validated by >87% occupant satisfaction. Reduce fan and chilled water energy use by 18–25% across monitored AHUs. Preserve indoor air quality**,** with CO_2 levels remaining under 800 ppm in >95% of monitored zones. The reprogramming of airflow setpoints was executed entirely via the Honeywell Enterprise Building Integrator (EBI), which controlled damper operation, static pressure, and supply air temperature across six AHUs. This confirms that existing control systems have untapped potential that can be unlocked without hardware modification, provided design teams are willing to reevaluate conservative assumptions. Control logic rationalization, such as reducing static pressure setpoints, limiting minimum airflow, and modulating fan speed based on real-time zone demand, are especially relevant in high-ambient environments where cooling systems run for 10–11 months annually.

VAV performance in hot climates is often affected by internal heat gains from lighting and equipment, as well as solar radiation. The study found that zones with south-facing glass façades or large perimeter exposures often exhibited higher damper positions even under reduced setpoints. This indicates the importance of integrating passive solar control, shading strategies, and high-performance glazing into building envelope design. By reducing the zone cooling load, envelope improvements can help align minimum airflow demands more closely with actual ventilation and comfort requirements, making VAV rescheduling more universally viable. Air mixing challenges at lower flows remain a concern in high-ambient settings. However, this study provides evidence that with proper diffuser selection (e.g., overhead swirl diffusers), acceptable ADPI values (>94%) can still be achieved at 25% minimum airflow. This directly challenges the conventional belief, often cited by diffuser manufacturers, that comfort cannot be sustained below 30–50% flow. It invites a rethinking of diffuser sizing and placement in new designs where airflow minimization is a design goal.

ASHRAE Standard 55 (thermal comfort) and 62.1 (ventilation) are frequently used to inform HVAC design (2004, 2022). However, these standards do not prescribe minimum VAV airflow values, leaving them to practitioner judgment or local codes. In high-ambient regions, this ambiguity has resulted in over-conservative airflow settings. This study's findings suggest that it is technically safe and thermally acceptable to revise airflow minimums downward, even in challenging climates. National codes and green building standards in Gulf countries (e.g., MEW's energy efficiency codes or Qatar's GSAS) should be updated to: mandate BAS-integrated airflow optimization strategies, encourage data-driven control refinement over design life, and include occupant satisfaction benchmarks as compliance indicators.

Subsidized electricity in countries like Kuwait masks the true cost of inefficient HVAC operation. By showing that there is considerable energy savings possible, as presented in section 5.6, without retrofits, this study provides a fiscal argument for utilities and ministries to promote VAV optimization in both public and private buildings. For example, AHU 10 in Building 2 showed a 25.4% drop in annual cooling power consumption post-rescheduling. Scaled across Kuwait's public sector building stock, such savings could result in tens of millions of kWh annually, reducing peak load demands and deferring capital-intensive power plant expansions.

This study shows that energy savings were achieved via Honeywell EBI R410.2 BAS software, no additional sensors, controllers, or communication infrastructure were required. This underscores that smart HVAC control is a software problem, not a hardware one. Implications for designers and facility managers include, ensure BAS platforms are fully unlocked for operational tuning, train facility engineers to monitor damper behaviors, review zone feedback, and adjust control loops regularly and adopt predictive algorithms or machine learning to optimize VAV airflow based on occupancy, weather, and internal loads. Findings from damper behavior showed several VAV boxes running at 100% damper opening unnecessarily (such as VAVs B170, F41, and F56). This indicates malfunctioning zone sensors, poor tuning, or faulty damper actuators**.** Advanced FDD platforms could detect such anomalies early, trigger alerts, and auto-adjust airflow commands to avoid overcooling. Integrating rescheduling with proactive maintenance regimes is essential in high-ambient regions where HVAC systems operate continuously for most of the year.

One surprising finding was that 56.98% of respondents reported feeling cold in their offices, even during peak summer periods. Only 10.61% felt warm. This highlights a cultural and behavioral mismatch between thermal expectations and system settings in GCC countries.

Implications include, allowing localized user control over temperature setpoints and airspeed, educating users on adaptive comfort principles and realistic expectations, and using feedback-informed control loops (e.g., occupancy and comfort sensors) to balance comfort and energy goals. The study found that 42.29% of occupants were satisfied with air quality, 38.29% were neutral, and only 19.43% were dissatisfied. This indicates that lower airflow does not necessarily compromise IAQ perception, provided CO_2 concentrations and RH are controlled. By quantifying IAQ alongside thermal data, designers can move toward holistic indoor environmental quality (IEQ) control, not just temperature-based regulation.

Based on this study, the following recommendations are proposed for high-ambient climate building projects: Specify flexible VAV control systems that allow for dynamic rescheduling of minimum airflow via BAS platforms. Set default minimum airflow values to 25–30%, with zone-level overrides based on IAQ and comfort monitoring. Include occupant feedback loops in control logic to ensure comfort is not sacrificed in pursuit of energy savings. Prioritize zonal zoning, solar load mitigation (e.g., glazing, shading), and internal load management in architectural design. Integrate performance-based commissioning using real-time IAQ, damper, and energy data during design validation. Update building energy codes in hot-arid regions to mandate adaptive airflow control, not fixed setpoints.

This study delivers compelling evidence that HVAC system performance in high-ambient climates can be dramatically improved through intelligent control rescheduling, without the need for mechanical retrofits. By adopting lower diffuser airflow minimums, significant energy savings are achievable, up to 25% per AHU, with no compromise on occupant comfort or air quality. For policymakers, the results support a shift from prescriptive to performance-based regulation. For designers, they offer clear design principles for adaptive, occupant-centric control strategies. Moreover, for operators, the research reaffirms the value of active, data-driven system tuning in extracting efficiency from existing infrastructure. Ultimately, this work underscores that climate-responsive HVAC design is not only feasible but also necessary for meeting sustainability targets in high-ambient regions.

5.7. Broader Impact and Replicability

This research provides a replicable model that can be deployed across other countries in the GCC (Saudi Arabia, UAE, Qatar, etc.) with similar climatic and operational conditions. Key elements for replication include existence of centralized HVAC and VAV systems, presence of BAS platforms, institutional capacity to monitor and manage building systems. Moreover, this method can be applied not only to government buildings but also to hospitals, educational institutions, and airports, where VAV systems are prevalent and energy usage is intensive.

6. Conclusion

This study provides field-based evidence supporting the optimization of minimum diffuser airflow setpoints in VAV systems as an effective strategy for improving energy efficiency in hot-arid climates. Based on the analysis of two government office buildings in Kuwait, the following key conclusions can be drawn:

- Substantial Energy Savings: Reducing minimum airflow setpoints from 50% to 25–30% of design capacity resulted in HVAC energy savings ranging from 18% to 25%, particularly in fan and chilled water system loads.
- No Compromise on Comfort or IAQ: Despite the reduction in airflow, over 87% of surveyed occupants reported thermal comfort satisfaction, and monitored CO_2 concentrations remained below 800 ppm in more than 95% of occupied zones.
- Operational Feasibility: The strategy was implemented entirely through the existing BAS platform, without hardware modification, demonstrating the ease of deployment in existing buildings.
- Scalability and Relevance: The intervention is highly replicable in other institutional, commercial, and governmental facilities throughout the GCC and other regions with high cooling demands.
- Support for Policy and Regulation: The outcomes advocate for the inclusion of VAV airflow optimization in national building codes, energy audits, and performance-based energy policies, contributing to broader energy efficiency and carbon reduction goals.

In conclusion, minimum diffuser airflow rescheduling represents a technically sound, low-cost pathway toward sustainable building operations in climates where air conditioning is a dominant energy load. This research provides both quantitative and qualitative validation, offering a model for large-scale adoption in energy-intensive sectors.

The intervention method requires minimal infrastructure change, emphasizing its cost-effectiveness. The findings suggest that adjusting VAV minimum settings should be integrated into retrofit strategies for existing buildings seeking to improve energy performance. Future research could investigate dynamic airflow adjustment strategies linked with real-time occupancy and climatic conditions.

This study demonstrates that rescheduling minimum diffuser airflow setpoints in VAV systems is a viable, low-cost strategy for enhancing HVAC energy efficiency in hot-arid environments. The approach yielded significant energy savings, confirmed through simulation and statistical analysis, without compromising indoor environmental quality. The findings provide a foundation for broader adoption of airflow control strategies in commercial building operations across high-temperature regions.

The following recommendations were made based on this study. Incentivize VAV Optimization Audits: Governments and utilities should offer rebates or technical assistance for public and private institutions that conduct VAV optimization audits. Revise Building Codes: Include specific provisions on VAV minimum airflow optimization in building energy codes, especially for new construction and major renovations. Train Facility Managers: Provide training for HVAC operators and facility managers on implementing and monitoring such strategies via BAS platforms. Develop National Performance Benchmarks: Establish sector-specific benchmarks for HVAC energy intensity that account for control strategy optimization, encouraging continuous performance improvement. Building operators in hot climates should implement minimum diffuser airflow rescheduling as a standard energy conservation measure. BAS control settings should be reviewed at least biannually to optimize airflow rates in response to changing occupancy patterns. Minimum airflow setpoints can be safely reduced to 25–30% of maximum design values for similar climates and building typologies.

The future work in this regard can be the following. Seasonal Limitation: The study was conducted over the summer. Future research should assess performance over transitional seasons to identify if similar benefits hold during partial cooling loads. Occupancy Variability: Office buildings studied had relatively stable occupancy. Dynamic occupancy environments (e.g., retail or hospitality) may show different results. Advanced Control Integration: The study used static minimum setpoints. Integration with dynamic or demand-controlled strategies (e.g., occupancy-based resets or CO_2-based VAV modulation) may yield additional savings. Investigation of dynamic airflow control strategies linked with real-time occupancy and temperature sensors. Comparative studies across different building types (e.g., hospitals, schools, Mosques) in hot climates. Long-term impact analysis on equipment wear and maintenance requirements after minimum airflow reduction. Future research should explore the integration of adaptive control algorithms that automatically adjust minimum flow based on occupancy, weather forecasts, and comfort feedback. Future work should also explore integrating machine learning algorithms to continuously optimize setpoints based on occupancy prediction, weather forecasting, and zone-level comfort feedback.

This paper has shown that VAV airflow optimization through reduced minimum setpoints is not only technically feasible but also operationally beneficial and policy-relevant in hot-arid regions. The results support a transition toward smarter, software-driven HVAC control strategies that align with regional energy sustainability goals. This approach provides a bridge between the high-level ambition of national energy visions and the ground-level practices of building operations. By validating the approach through field data in one of the world's most cooling-intensive climates, this research sets a precedent for both academic inquiry and policy formulation in the domain of building energy efficiency.

Author Contributions

Conceptualization, K.J.S.; methodology, K.J.S., S.A., A.E. and R.A.; software, S.A and A.E.; validation, K.J.S., F.A. and S.A.; formal analysis, S.A. and A.E.; investigation, K.J.S.; resources, A.E., R.A. and S.A.; data curation, S.A.; writing—original draft preparation, K.J.S., A.E. and S.A.; writing—review and editing, K.J.S. and F.A.; visualization, A.E. and S.A.; supervision, K.J.S.; project administration, K.J.S.; funding acquisition, K.J.S. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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