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Impacts of HVAC cleaning on energy consumption and supply airflow: A multi-climate evaluation

Nasim Ildiri [a], Emma Biesiada [a], Tullio Facchinetti [b], Norma Anglani [c], Nouman Ahmed [c], Mark Hernandez [a,*]

[a] Department of Civil, Environmental and Architectural Engineering, University of Colorado, Boulder, USA
[b] Department of Electrical, Computer and Biomedical Engineering, University of Pavia, Italy
[c] Department of Industrial and Information Engineering, University of Pavia, Italy

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ABSTRACT

Energy-efficiency interventions are crucial for sustainable building operations to accommodate emerging indoor air quality (IAQ) criteria into their engineering life cycles. While several studies have addressed building energy consumption and IAQ considerations separately, few provide integrated analysis of these aspects in response to building hygiene practices. In response, this study evaluates the effectiveness of routine heating, ventilation, and air conditioning (HVAC) cleaning on energy consumption and supply airflow patterns in non-residential public buildings. This study juxtaposes HVAC energy consumption and ventilation performance before, during and after routine HVAC cleaning, across buildings situated in four different climate zones, while operating in cooling mode. Each site had nearly identical HVAC systems serving similar architectural features and occupational loads; these were segregated into an intervention (cleaned HVAC system) that could be compared to an otherwise identically operating HVAC (control system), which was not cleaned. Following prescriptive cleaning, HVAC systems exhibited significant energy consumption reductions and delivered higher airflows compared to their uncleaned counterparts. On average, intervention systems saved between 41 % and 60 % on conveyance (fan/blower) energy, with one exception, and supplied 10 % and 46 % more airflow compared to their uncleaned counterparts. This research demonstrates how a new generation of low-cost HVAC system monitors can compile Internet of Things (IoT) archives to show immediate energy consumption benefits associated with cleaning HVAC components and their associated ductwork serving relatively high occupancy commercial and educational spaces.

1. Introduction

Building operations consume nearly one-third of total global energy output, accounting for a significant contribution to CO_2 emissions worldwide [1]. In the United States, commercial and residential buildings account for about 40 % of domestic energy consumption [2]. Such energy consumption trends in the building sector are expected to continue due to population growth, urbanization, increases in high-density building developments, rising comfort demands, and emerging indoor air quality (IAQ) concerns [3]. Furthermore, emerging guidelines for improving ventilation and indoor air quality [4-7] are expected to increase building energy consumption budgets in the foreseeable future.

In the context of building services, HVAC-associated energy consumption is significant, accounting for nearly 50 % of total energy usage in U.S. commercial and public buildings [8]. Given this substantial contribution, enhancing HVAC performance can lead to significant societal energy savings [9]. HVAC systems continuously manage thermal energy transfer while mixing and replenishing fresh air through occupied spaces. Energy is primarily consumed for heating, cooling, ventilation, air filtration, distribution, as well as by supporting auxiliary components such as chillers, boilers, backup fans, and variable frequency drives (VFDs). These systems employ various components and mechanisms to manage indoor environmental conditions.

HVAC systems are often operated to manage thermal comfort while maintaining indoor air quality through conditioning and (re)circulating filtered fresh air to occupied spaces. Given the amount of time people spend indoors, building environments can significantly impact occupant comfort and respiratory exposure; thermal management and indoor air

* Corresponding author.
E-mail address: mark.hernandez@colorado.edu (M. Hernandez).

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quality are identified as one of the primary factors influencing the comfort, wellness, and productivity of building occupants [10-12]. Ducted HVAC systems with integrated filters help reduce the indoor load of ambient particulate matter (PM) in the environments they serve. Depending on the design and operation of these systems, in-line filters can further reduce the PM load associated with occupant shedding and indoor particle resuspension [13]. However, in some cases, the HVAC system itself can become both an acute and chronic source of PM and volatile organic carbon (VOC) emissions [14-16].

Conventional HVAC operations result in the gradual accumulation of particulate matter (PM) on the surfaces of different HVAC components [17,18], often reducing the energy efficiency of these systems over time; both heat transfer inhibition and cumulative airflow drag are responsible for this phenomenon [19,20]. While the PM fouling of any single HVAC component may lead to minor energy efficiency losses, the energy impacts can become significant when considering cumulative losses across all HVAC components, especially in larger buildings with expansive ductwork [21]. Moreover, design factors, faulty installation, operational paradigms and inadequate maintenance of HVAC system components can contribute to increased respiratory PM exposures, some of which can influence allergenic and hypersensitive responses from building occupants [22,23]. For instance, soiling of ductwork downstream of cooling coils and other areas that experience relatively high humidity or large humidity swings, often support microbiological deposition and activity, which can lead to negative operational and maintenance outcomes, including corrosion, odors, compromised insulation, and potential respiratory pathogen sources [24].

1.1. Review of Relevant literature

While numerous studies emphasize the importance of HVAC operation and maintenance for improving building energy performance [25-27], there is a lack for research investigating the effectiveness of building hygiene practices, in particular HVAC cleaning, on immediate and long-term energy savings potential for higher occupancy buildings. Since the U.S. Environmental Protection Agency (EPA) released the 1997 position paper on residential duct cleaning [28], only a limited number of studies have systematically examined the potential impacts HVAC system component cleaning can have on energy consumption patterns—a few of which included any accompanying IAQ survey.

Zhai and Johnson examined the effects of pressure drops within HVAC systems—caused by filter fouling, duct obstructions, and leakage—on fan energy consumption [29]. Using full-scale laboratory experiments, the authors observed that increased pressure drops, particularly from fouled filters, can raise energy consumption by up to 45.5 % when duct leakage is also present. To simulate increased pressure from fouling, the study introduced materials like linen sheets and wooden objects within the ductwork to mimic dust and obstructions, while foam board particles were added to elevate pressure drops across the filter. In a related study, Wilson et al. [30] examined the energy savings associated with cleaning coils and filters in constant air volume HVAC systems within single-family residential and small office buildings. Using a validated computer model to simulate varying levels of fouling in multiple climates, they found that while fouling affects both air conditioner and furnace energy use, anticipated energy savings are minimal for single-family residential buildings and may be negative for small office buildings based on fouling levels reported in the literature. They also emphasize the importance of regular cleaning and proper maintenance of constant air volume HVAC systems that introduce outside air for ventilation, to ensure that the systems maintain their designed ventilation rates.

In another study, Lin et al. [31] conducted an analysis of energy consumption patterns in United Arab Emirates buildings, with a specific focus on the operation and maintenance of building systems. Their findings indicate that, among other parameters, the cleanliness of air conditioning systems and the surface conditions of chillers are critical factors that significantly influence building energy consumption. In another study, Siegel and coworkers [32] critically examined particle deposition on evaporator coils and related effects of indoor particle and dust concentrations on coil fouling rates. Their results suggested that regular coil cleaning should be an integrated priority of residential air conditioning maintenance procedures to increase evaporator coil lifetimes and overall system energy efficiency. This observation likely extends to commercial HVAC hygiene as well.

While the quantity and thermodynamic properties of supply air have been the conventional focus of HVAC operations, the quality of air supplied to occupied spaces has received increased attention. Despite this, few studies have directly examined the effects of HVAC cleaning on indoor air quality. Ahmad et al. [22] looked at the effectiveness of three commercial HVAC duct cleaning processes in reducing airborne particulate matter (PM) and bioaerosols in residential homes. Results showed that during cleaning, PM and bioaerosol concentrations increased, suggesting that cleaning processes can disturb particle-associated pollutants. However, post-cleaning bioaerosol concentrations were significantly lower, indicating that cleaning has effectiveness on reducing subsequent respirable particle exposures over longer terms. In another study, Simbada et al. [16] analysed the bacterial DNA from HVAC filter dust collected in two university buildings. The results revealed the presence of potential pathogens, including the retention of antibiotic-resistant bacteria in HVAC systems, potentially posing health risk to occupants. They advised regular cleaning and disinfection of all HVAC systems to prevent potential pathogen accumulation and reduce occupants' potential respiratory exposures.

1.2. Contribution and research hypotheses

While existing literature highlights the potential of HVAC system management for enhancing energy savings, the actual effectiveness of HVAC system cleaning, and its influence on the interplay between energy consumption and indoor air quality should be considered [33]. Previous research has primarily relied on computer modelling and theoretical approaches to assess the effects of building hygiene practices on energy consumption, while an accompanying pool of actual field data are limited or not peer-reviewed if available. Studies often depend on controlled laboratory experiments, typically focusing on simulated cleaning processes for specific HVAC parts or components rather than on comprehensive, full-scale cleaning of ducts and other system elements. This approach may overlook key factors such as occupant activity, equipment aging, and actual duct conditions, including leaks—all of which can significantly impact HVAC performance. Additionally, previous studies on this topic have often focused on a limited sample of buildings, observed over relatively short durations within a single climate zone.

While existing literature predominantly focuses on residential and small office buildings, our study addresses medium-density commercial and public buildings. In response, this study demonstrates a scalable path to assess the effectiveness of HVAC system cleaning on energy consumption, concomitant with conditioned supply airflow monitoring, in medium-to-higher, non-residential buildings. By conducting our study in real-world settings, we aim to better capture actual building operation conditions and their effects on energy efficiency and supply airflow. A time-resolved examination of energy-related parameters and supply flow rates in buildings situated in four markedly different climate zones is reported— juxtaposing ventilation performance before, during and after staged HVAC cleaning using widely-accepted building hygiene practices. Each site chosen had nearly identical HVAC systems serving similar occupied areas, which were segregated into an intervention (cleaned system) for comparison with an otherwise identically operating control system that was not cleaned.

This report tests the hypotheses regarding the impact of building hygiene practices, specifically HVAC cleaning interventions, on energy consumption and indoor air quality as measured by supply airflow. We propose that cleaned HVAC systems will consume less energy than their uncleaned counterparts while delivering higher airflow rates. We report some of the immediate energy consumption benefits associated with full-scale HVAC system cleaning in a variety of medium-to-higher occupancy building types across several climate zones (in cooling mode). While the absolute energy consumption benefits are relative to each site, we observed consistently improved ventilation performance patterns across all sites. This suggests that beneficial effects can be realized by cleaning all HVAC system components, but notably including the conveyance system itself (ductwork) and enhanced VAV operational stability.

2. Methods

2.1. Site selection and system Specifications

Given the significant impact of physical geography, urban effects and local climate conditions on HVAC system behaviour and its energy consumption [34], this study selected four groups of buildings across the United States and Europe, each representing conditions in a major climate zone with a significant population: In the United States, Johnson, Vermont represents the temperate northeast climate (Zone 6A: Cold–Humid); Pearl, Mississippi represents the sub-tropical southeast (Zone 2A: Hot–Humid); Boulder, Colorado, represents the arid mountain west (Zone 5B: Cool–Dry); and Pavia, Italy represents a temperate climate, 4A (Mixed–Humid) [35]. Studies have revealed that building type [36] and occupant activity [37] can affect HVAC system loads and dynamics. In this study, building functionalities span a diverse range of medium-to high occupancy settings, from an office building in Johnson, Vermont, to a daycare/gym facility in Pearl, Mississippi, as well educational spaces in Boulder, Colorado and Pavia, Italy. Fig. 1 displays locations of the buildings analysed in this study. Both occupied and unoccupied conditions were considered.

For this study, two nearly identical Air Handling Units (AHUs) were deliberately selected at each site for practical comparative analysis (control vs. intervention). The site selection was guided by the following criteria: first, they had to possess a minimum quantity of ducts with varying lengths and turns, in order to be generalized to an average medium-density service system duct system. Additionally, access to blueprints or simplified drawings of the HVAC system was required. It was also essential that the chosen systems did not incorporate variable speed fans, or if they did, the ability to operate them at a fixed speed for the duration of the study was mandated. Furthermore, a duplicate or a similar system in immediate proximity, serving a similar architectural space, was necessary for comparative analysis. Moreover, the systems had to be free of excessive nuances or variables like numerous reheat coils or inline restrictions. Finally, the location of these sites had to be dependable to ensure uninterrupted access throughout all scheduled phases of a cleaning response study. The cooling capacities of the HVAC systems ranged between approximately 10 tons (at the Vermont site) to 30 tons (at the Italy site).

To maintain consistency during this cleaning intervention study, any Variable Air Volume (VAV) controllers, where present, were deactivated (locked open). Ensuring that filter conditions did not impact the measurements in either control or cleaning intervention systems, any existing filters were replaced with new filters of the same type, before commencing cleaning protocols. Other key considerations encompassed formal facility manager engagements, scheduling all monitor installations, cleaning and subsequent operations in collaboration with building owners and managers. Furthermore, it was imperative that

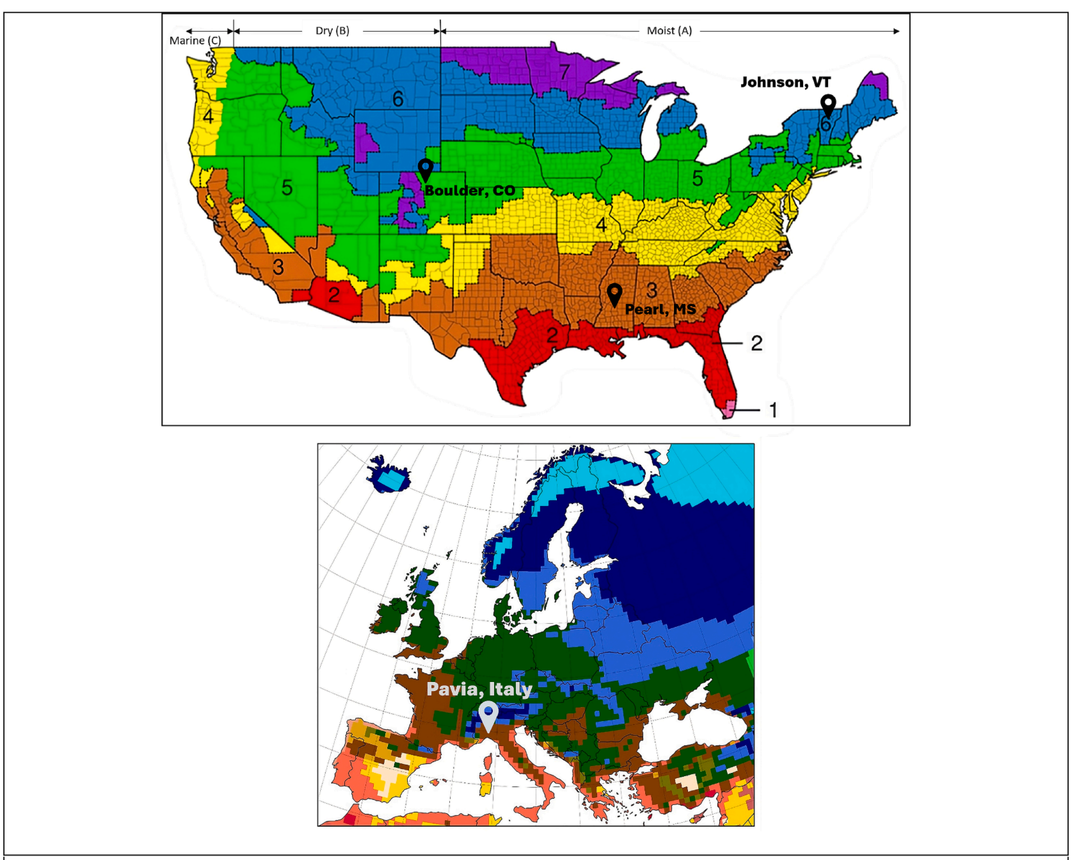

Fig. 1. Building sites participating in this study superimposed on a climate zone map as designated by ASHRAE [35]. Top: United States climate zones with three study sites including Boulder, Colorado (Zone 5b, Cold/Dry); Johnson, Vermont (Zone 6A, Cold/Humid); Pearl, Mississippi (Zone 3A Warm/Humid). Bottom: Europe climate zones, Pavia, Italy (Temperate/Warm).

cleaning contractors possessed the necessary training to install HVAC system energy monitors, sensors and accurately measure supply airflows at the registers. During the cleaning process, the supply and return duct systems, including registers, were thoroughly cleaned, ensuring that any dampers were left in their pre-cleaning positions. All HVAC system components, including fans/blowers, heat exchangers, and evaporator/condenser coils, were cleaned following industry standards [38]. The study timeline, along with a summary of climatic conditions at the building sites participating in this study, is listed in Table 1. Cleaning schedule staging and details for each site are available in the Supplementary Materials (A 1–A 4).

2.2. Data collection

The monitoring and data collection process was consistent and uniform for both control and intervention systems at each site. The following sensors were deployed in both intervention and control sides across at the four different sites (Fig. 2).

R&T-500 Series (T&D) sensors [39] were used at the Vermont and Mississippi sites for measuring energy (RTR-505-P) and pressure (RTR-505-mA, with 0.05 mA + 0.3 % of reading inaccuracy) values. Data from these sensors were accessed via the vendors' cloud server, T&D Web-Storage Service [40]. Measurements from the sensors were reported at an hourly frequency.

At the Colorado site, a Dwyer Series 607 Differential Pressure Transmitter [41] was used to assess pressure drop, the Keyence FD-R Series Clamp-on Flow Meter [42] measured flow rate (temp accuracy = ±3 °C, flow accuracy = ±2 %), the Dwyer Series RHP Humidity and Temperature Transmitter [43] monitored humidity (±2 % inaccuracy) and temperature (±0.3 °C inaccuracy), and the WND series WattNode Wide-Range Modbus [44] served as the electric power meter (±0.5 % inaccuracy). Data from these sensors were accessed through the vendor's cloud server, Attune [45], with a data reporting frequency of every minute.

At the Italian site, the SmartDHOME [46] sensor family was utilized to measure energy consumption, providing real-time data monitoring capabilities through MyVirtuoso Home [47] software. The Ultrasonic Heat/Cool Meter was deployed to measure the flowrate and temperature of cooling water (±1 % inaccuracy). The energy consumption of fans (blowers) was measured using a three-phase inductive energy meter. For monitoring differential pressure, temperature, and relative humidity, as well as capturing real-time photos from the interior of HVAC system ducts and AHUs, REMOTAIR [48] sensors were utilized. Equipped with cameras installed in AHUs and ducts, REMOTAIR sensors captured photos multiple times per day, enabling the ongoing tracking of particle deposition conditions within the HVAC system.

At all sites, an industry standard method was used to measure and record the volumetric flow through each supply register using a four-quadrant measurement or flow hood. While the energy consumption and differential pressure within the HVAC systems were continuously measured, supply airflow was intermittently measured before, during, and after the cleaning process, with data recorded for both control and intervention systems. Measurements were conducted according to the National Environmental Balancing Bureau (NEBB) "Procedural Standards for Testing, Adjusting, and Balancing of Environmental Systems" [49]. Similar to the energy and air quality sensors, the supply airflow measurement process was consistent and uniform for both control and intervention systems at each site, ensuring the basis for stringent statistical comparisons.

Table 1
Table summarizing climatic zone and project timeline at the building sites participating in this study.

Location	Climatic condition	ASHRAE climate zone	Start date	End date
Johnson, VT	Temperate Northeast	6A: Cold – Humid	Jul 17, 2019	Sep 1, 2019
Pearl, MS	Sub-Tropical Southeast	2A: Hot – Humid	Jul 17, 2020	Oct 10, 2020
Boulder, CO	Arid Mountain West	5B: Cool – Dry	Aug 17, 2022	Oct 5, 2022
Pavia, Italy	Temperate	4A: Mixed – Humid	Jun 15, 2023	Aug 4, 2023

2.3. Data analysis

Both descriptive and inferential statistical methods were applied to analyse energy consumption and ventilation performance data. This analysis was structured to investigate the energy-related response of routine HVAC system cleaning, as well as to identify common patterns in system performance dynamics within these non-residential public buildings. Statistical analyses were conducted utilizing the R programming language within the RStudio environment [50], with visual presentations generated using R-compatible libraries [51].

The data analysis procedures were standardized across all locations. For the primary analysis, data collected from 8 am to 6 pm (local time zone) on regular working days were incorporated into the study. Sensor data from public holidays and system cleaning days were omitted from the analysis. Additionally, instances of technical malfunctions in either the control or intervention systems, such as refrigerant leaks, necessitated immediate attention from maintenance personnel, resulting in the shutdown of either the entire system or specific faulty components. Data collected on these days were also excluded from the analysis. Data from both the control and intervention (cleaned) systems were collected during all the different cleaning phases, which were consistently staged to isolate cleaning effects on the heat transfer equipment, conveyance system (ducts) and fans (blowers). Differential pressure across the HVAC system was continuously measured. Data obtained prior to cleaning served as foundational baseline(s).

Cumulative daily energy consumed by fans, blowers, and cooling equipment, alongside differential pressure values, were computed for both the control and intervention systems. The trends of these variables over the duration of the project were analysed using widely accepted statistical regression practices. A reporting model was constructed using the linear model function in base R to identify trends in energy consumption and ventilation performance variables [52]. This function formulates regressions with variance. In the context of this study, the regression model described linear relationships between the energy usage for cooling, air conveyance, and differential pressure (outcome variables) and the observation days across the project timeline (predictor variable). This model was individually fitted to the variables of interest in both the control and intervention systems, which were then compared.

To assess whether HVAC components in control and intervention systems at each site differ significantly, an analysis of covariance (ANCOVA) was conducted across the respective cleaning stages at each site. ANCOVA is a statistical technique that combines analysis of variance (ANOVA) with linear regression [53] for normally distributed data, which applies to the present study. In the context of examining regression variances between control and intervention systems, ANCOVA tests determined whether observed distinctions remain significant after accounting for covariates, thereby offering a more refined comprehension of the relationship between any independent and dependent variables. A significant interaction term between the experimental condition and the covariates indicates that the regressions for the control and intervention groups are not parallel, suggesting disparate relationships between the independent and dependent variables across the two groups. In this case, the ANCOVA fitted a linear model to predict energy consumption based on the observation day, system type, i.e., control or intervention, and the interaction between these two factors, i.e., observation day and system type. Eq. (1) shows an example of how the ANCOVA model was constructed in R for the value of interest:

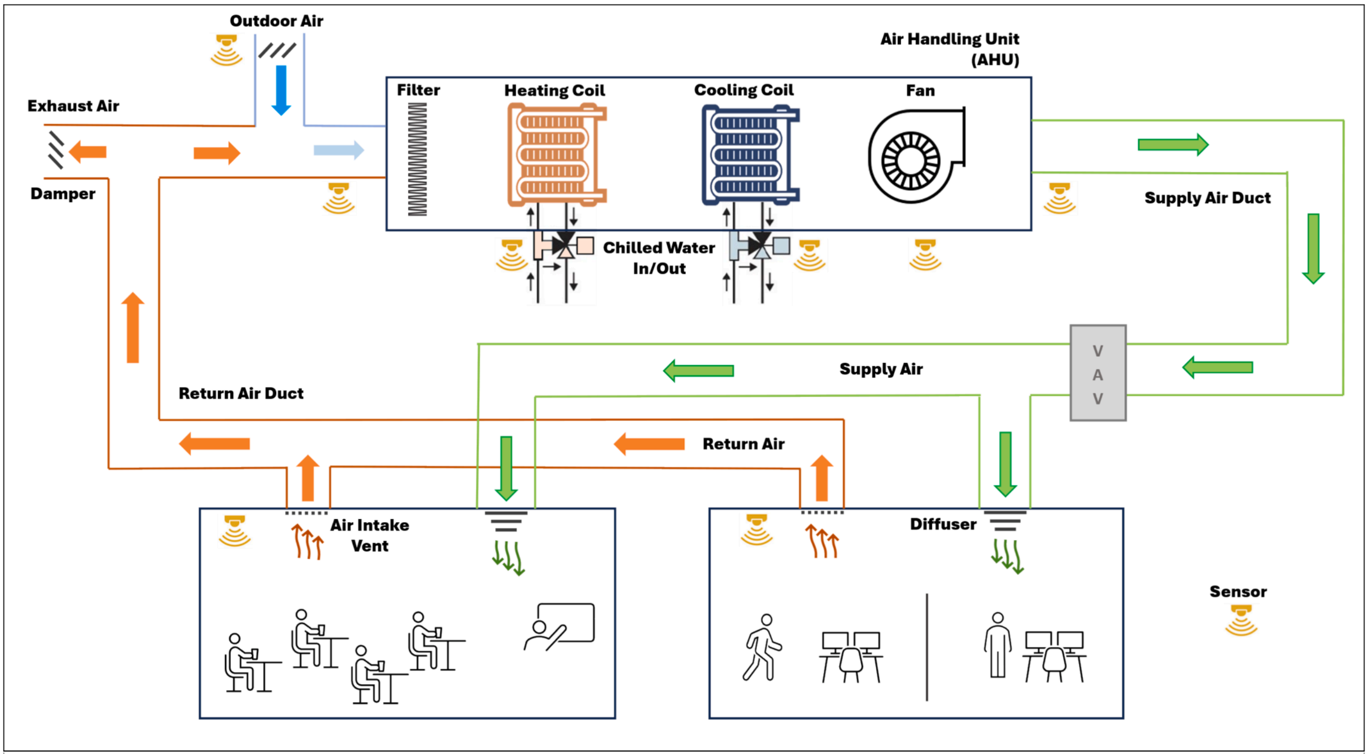

Fig. 2. Schematic of air handling units (AHU), sensor networks, duct work and occupied spaces of that typically observed in this study. Energy consumption sensors were installed on all fans and heat transfer equipment. Pressure sensors were installed in ductwork immediately upstream and downstream of the AHU. Thermodynamic sensors (T and RH) were installed in the occupied spaces and immediately adjacent to outdoor (fresh) air intake.

$$ANCOVAModel = LinearModel\begin{pmatrix} DependantVariable \\ ObservationDay + SystemType \\ +ObservationDay{*}SystemType \end{pmatrix}\# \quad (1)$$

The significance levels for the linear regression models were classified as follows: highly significant ($p < 0.001$), very significant ($p < 0.01$), significant ($p < 0.05$), marginally significant ($p < 0.1$) and not significant ($p \geq 0.1$). The p-value in this context indicates the probability of observing the difference in slopes between the control and intervention groups, assuming there is no true difference between them, with smaller p-values suggesting stronger evidence against the null hypothesis.

Additionally, we compared the daily energy required for air conveyance (i.e., fans and blowers) in both the intervention and control systems on each observation day, and adapted a method similar to that of Zhai and Johnson [29] to calculate the percentage of potential relative energy savings, as shown in Eq. (2):

$$PercentofRelativeEnergySaving = (Energy_{control} - Energy_{intervention})/Energy_{control} \quad (2)$$

To assess the impact of HVAC system cleaning on supply airflow, measurements from the control side were subtracted from those of the intervention side and plotted over the time for each project site. This enabled monitoring of how differences between intervention and control measurements changed throughout each cleaning phases. To better quantify the difference between the control and intervention systems following each stage of cleaning, we calculated the percentage increase in supply airflow rates using Eq. (3) [30]:

$$PercentofRelativeIncreaseinSupplyAirflow = (FlowRate_{intervention} - FlowRate_{control})/FlowRate_{control}\# \quad (3)$$

Changes in supply airflow at each stage of the cleaning compared to the previous cleaning stage was also studied to identify the cleaning stage that were most impactful as judged by supply airflow rates.

3. Results

The influence of routine HVAC system cleaning on energy use and supply airflow in public, non-residential buildings was studied. A detailed, time-resolved analysis was conducted on energy and airflow metrics in buildings grouped in the various climate zones is reported below. This section details the observed patterns in energy consumption, changes in supply airflow rates, and other overall impact of the HVAC cleaning practiced here. The structure of the Results and Discussion section is as follows: The impact of HVAC cleaning on energy consumption at each site is presented chronologically. Next, an analysis of supply airflow across all sites is provided. Other unanticipated benefits arising from the cleaning process, i.e., system stability, are then discussed.

3.1. Energy consumption

An overall reduction in energy consumption in fans and cooling energy was anticipated and quantified, primarily due to the decreased cooling loads resulting from the transition to cooler outdoor temperatures as the studies progress from summer to fall seasons at all sites. This expectation also applies to differential pressure reductions. The cleaning process commenced during the peak load of HVAC systems, coinciding with the peak of warmest season in each location. The sites and associated results are res described in the order studied, during summers of 2019, 2020, 2022 and 2023 (2021 was a study hiatus due to COVID-19 building shutdowns).

3.1.1. Johnson, VT

The analysis of the first location (2019), Vermont, examined the cumulative daily energy consumption of the blower, cooling, and daily average differential pressure over the duration of this project. The daily energy use by blowers in both control and intervention systems, calculated based on the methodology in Eq. (2), indicates that daily relative energy savings ranged between 43 % and 50 %, with an average of 44 % over the study duration.

Parallel regression analysis of data from both the control and intervention systems suggests that although the cumulative daily energy consumption of the blower in the intervention system increased at a higher rate compared to the control system, the respective increases were not statistically significant. The relatively high p-values in both groups and the ANCOVA analysis indicated that routine HVAC system cleaning did not significantly impact the blower's energy consumption in this setting (Table 2).

For the energy consumption used for cooling by the main compressor, both the control and intervention systems exhibited negative slopes, indicating a decrease in energy consumption over the season observed. These data indicate that while there is a statistically significant decrease in energy consumption for cooling in both systems, which is consistent with the prevailing weather pattern, the routine cleaning of the HVAC system did not result in a significant consumption rate differences when comparing the control and intervention thermodynamic heat transfer performance. Additionally, the analysis showed a slight decrease in the daily averaged differential pressure in the cleaned system over time. However, no significant difference between the control and intervention systems was observed.

In summary, the primary system results from the Vermont office site location suggest that routine cleaning of HVAC systems did not significantly affect the energy consumption patterns of the conveyance or the cooling system, nor did it significantly impact the differential pressure in the system. The lack of significant energy performance differences between control and intervention systems implies that other factors may play a more crucial role. At the Vermont site, this manifest in differences in the number and duration of back up compressor recalls between the cleaned and control systems.

Here, both the control and intervention air conditioning systems featured a backup compressor, which were frequently brought into supplementary service to meet cooling demand. A notable observation following HVAC cleaning was the reduced startup frequency of backup equipment in the intervention (cleaned) side (Fig. 3). A comparison between the control and intervention systems revealed that the backup compressor in the intervention side was activated 47 % less frequently than its counterpart in the control side. This reduction in back-up system startup frequency could potentially extend equipment lifetime and reduce maintenance costs.

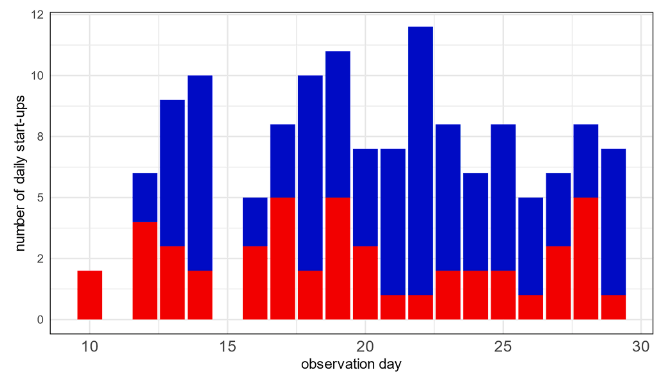

Fig. 3. Daily service recall frequency of back up air conditioning compressors supporting control (■) system and intervention system (■) in response to HVAC system cleaning in Johnson, VT office building.

Table 2
Table summarizing analyses of variance outcomes of selected energy consumption and differential pressure comparisons at the different sites. The significant codes used are as follows: *** indicates $p < 0.001$, ** indicates $p < 0.01$, * indicates $p < 0.05$.

Location	Parameter	System	Slope	Intercept	ANCOVA slope difference
Johnson, VT	Blower energy	Control	8.76	49706.08 ***	NS
		Intervention	14.10	27687.89***	
	Cooling energy	Control	−231.93*	23299.07***	NS
		Intervention	−231.36*	22036.38***	
	Cooling energy (backup)	Control	−48.30	4053.25***	*
		Intervention	−212.05***	5477.13***	
	Differential pressure	Control	0.00057	6.40***	NS
		Intervention	−0.0020	5.85***	
Pearl, MS	Blower energy	Control	1.73	528.63***	**
		Intervention	−6.58***	436.43***	
	Cooling energy	Control	−11.80*	1738.63***	*
		Intervention	−32.85***	1822.80***	
	Differential pressure	Control	−0.0041**	4.76***	*
		Intervention	−0.010***	4.73***	
Boulder, CO	Fan energy	Control	−0.95	4397.56 ***	***
		Intervention	33.17***	5208.38***	
	Fan energy (after hours)	Control	−4.73	3764.25***	***
		Intervention	−55.77***	6842.88***	
	Cooling energy	Control	−171.03***	6576.50***	*
		Intervention	−329.43***	17810.20***	
	Cooling energy (after hours)	Control	0.17	209.40**	***
		Intervention	−27.02***	2366.48***	
	Differential pressure	Control	0.00037	1.42***	***
		Intervention	0.011***	1.17***	
Pavia, Italy	Fan energy	Control	2592.6**	117184.1***	***
		Intervention	−38.09	57732.24***	
	Cooling energy	Control	−32.49	10821.42***	NS
		Intervention	−16.24	17407.68***	

Furthermore, considering the energy consumption of backup equipment (Supplementary Material, A 5), the comparison of power between the control and intervention systems revealed a significant energy consumption difference: the compressor on the intervention side demonstrated a substantially greater reduction in energy consumption compared to the control. These energy consumption patterns suggest that routine HVAC system cleaning may have a notable impact on the energy usage of backup compressors on these otherwise identical systems with similar architectural features and occupancy.

3.1.2. Pearl, MS

A similar analysis was done on the daily cumulative energy consumption of the blower and cooling systems, as well as the daily average differential pressure in the Pearl, Mississippi location. The intervention group included two blowers, while the control group had three blowers; additionally, both control and intervention HVAC systems were equipped with two compressors each. For the blower energy consumption, the intervention system exhibited a significant energy consumption decrease, while the control system showed no such performance changes (Fig. 4). The daily energy use by blowers in both control and intervention systems, calculated with the methodology in Eq. (2), indicates that daily relative energy savings ranged between 4 % and 94 %, with an average of 41 % over the study duration. ANCOVA analysis also revealed a significant energy consumption difference between the control and intervention systems ($p < 0.01$), indicating that the routine HVAC cleaning resulted in a notable reduction in energy consumption (Table 2).

For the energy consumption patterns associated with the air cooling equipment, both systems showed significant decreases over time, consistent with the prevailing weather pattern; however, the intervention system demonstrated a steeper decrease compared to the control system. ANCOVA analysis confirmed a significant difference in slopes ($p < 0.05$), suggesting that routine cleaning led to a more pronounced reduction in cooling energy consumption.

In terms of daily average differential pressure (supply and outdoor air), both systems exhibited significant decrease over time, with the intervention system showing a steeper decrease compared to the control system. ANCOVA analysis indicated that routine cleaning resulted in a substantial reduction in differential pressure following individual stages of the cleaning process as well as the cumulative outcome.

The results from the Mississippi location demonstrate that routine cleaning of HVAC systems can significantly reduce energy consumption for both the blower and cooling systems, as well as lowering the differential pressure across this system.

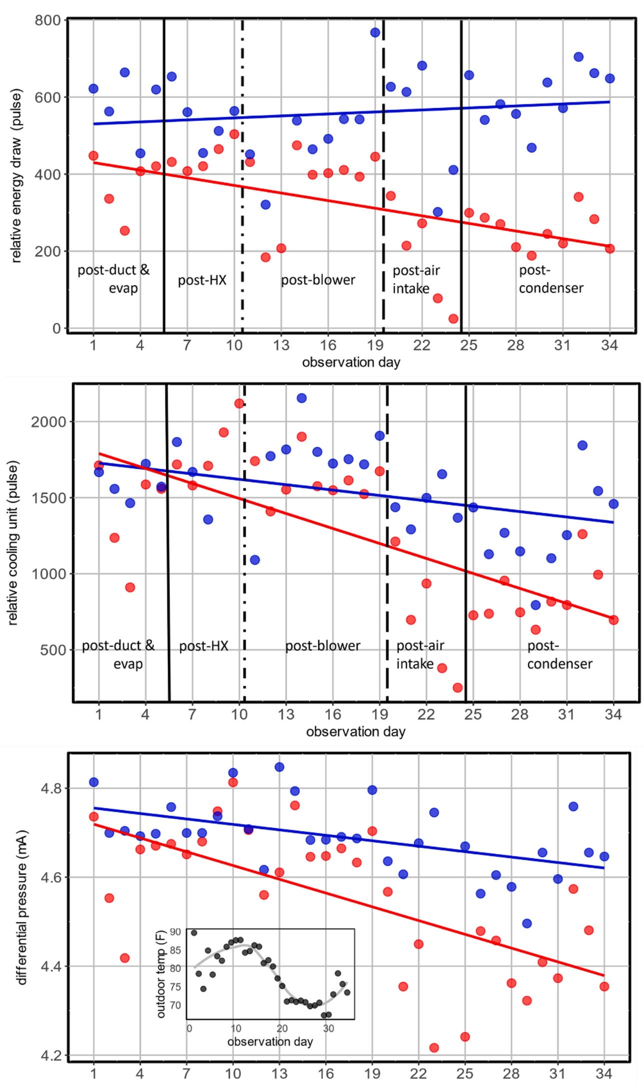

Fig. 4. Relative HVAC performance of control (-●-) system and intervention system (-●-) in response to stages of HVAC system cleaning in a Pearl, MS day care school building. **Top:** relative fan energy draw (normalized voltage pulses); **Middle**: relative cooling energy draw (normalized voltage pulses); **Bottom:** differential pressure across heat transfer equipment (normalized current (mA)); **Bottom inset**: outdoor temperature during observation period.

3.1.3. Boulder, CO

In the analysis of the Colorado location, the daily cumulative energy consumption for the fan and cooling systems, as well as the daily average differential pressure, were examined for both the control and intervention systems. Cooling for this location was provided by a remote waterchiller system.

Concerning blower energy consumption, the intervention system demonstrated a significant increase over time and used between 20 % to 37 % less energy compared to control system on daily basis (Eq. (2). Meanwhile, the control system exhibited a non-significant decrease (A 6). Despite the increase in blower energy consumption, the intervention system showed a greater reduction in cooling energy consumption over time. Both systems showed significant decreases in terms of cooling energy consumption, consistent with the prevailing weather pattern, with the intervention system demonstrating a steeper decrease compared to the control system. ANCOVA analysis suggested that routine cleaning could be associated with a more pronounced reduction in cooling energy consumption at this location (Table 2).

Regarding daily average differential pressure, both systems exhibited significant increases over the study period, with the intervention system showing a much steeper increase compared to its control. Although the differential pressure (DP) of the intervention system remained lower than that of the control over an extended period, it increased toward the end of the cleaning phase and into the heating season (as indicated by outdoor air temperature data), allowing the system to provide conditioned air more effectively. An examination of supply air temperature and humidity revealed that the control system was unable to provide an appropriate temperature of conditioned air to the indoor spaces it served, while the cleaned system was capable of supplying air at desired conditions (A 7). This discrepancy may explain why the cleaned system consumed more conveyance (fan) energy compared to the control system, as the control system was unable to meet the load demand (A 8).

Unlike the other locations, the Colorado site HVAC systems remained fully operational during both occupied and unoccupied periods. Therefore, both occupied and unoccupied air conditioning data from the Colorado site was included for this aspect of the analysis. The HVAC system in Colorado featured integrated VAV controllers, which were initially deactivated ("locked open") during the primary study to maintain consistent airflow rates into the rooms. VAV terminal boxes modulate VAV damper positions to regulate both the supply airflow and a "reheat" region to help better maintain local zone temperatures. Recent research indicates that VAV configurations can influence fan power cycles as well as cooling and heating energy consumption [25]. As a result, VAV boxes were initially deactivated during and after the cleaning process. However, once sufficient post-cleaning data was collected to compare sensor measurements between intervention and control systems, they (VAVs) were subsequently (re)activated and monitoring continued assess the system's performance in regular operational mode, i.e., with all VAVs activated.

Regarding fans energy and cooling, the intervention system at the Colorado site exhibited a steeper negative slope compared to the control (Fig. 5, A 8). The comparison of slopes between the control and intervention systems yielded significant differences. The intervention group, apparently benefiting from cleaning, displayed a substantially greater reduction in energy usage compared to the control system when considering the prevailing weather pattern. This finding underscores the potential efficacy of routine cleaning in improving energy efficiency considering both occupied and unoccupied hours.

3.1.4. Pavia, Italy

Similar analysis was done on the daily cumulative energy consumption of the blowers and cooling system in University of Pavia buildings. For blower energy consumption, the control system exhibited a significant positive slope, indicating an increasing trend in energy usage over this seasonal time. In contrast, the intervention system displayed a negative slope (Fig. 6). The comparison of slopes between the control and intervention groups yielded statistically significant differences considering the prevailing weather pattern during the end of the cooling season (Table 2). The differences in daily energy use by blowers in control and intervention systems at the Pavia site, calculated based on Eq. (2), shows that daily relative energy savings ranged between 39 % and 67 %, with an average of 60 % over the study duration (Fig. 6).

For the energy consumption used for cooling, both the control and intervention groups exhibited insignificant changes over time. While routine HVAC system cleaning demonstrated a significant reduction in blower energy consumption, its impact on cooling energy consumption was not significant (A 9). These findings highlight the importance of considering all system characteristics and environmental factors when evaluating the efficacy of cleaning interventions.

3.2. Supply airflow

In this study, a systematic method was used to measure and document the supply air from each supply register at each site (in cubic feet per minute, or CFM). Supply air measurements were obtained before, during, and after the cleaning process, with data recorded for both control and intervention systems. All sites had non-operable windows

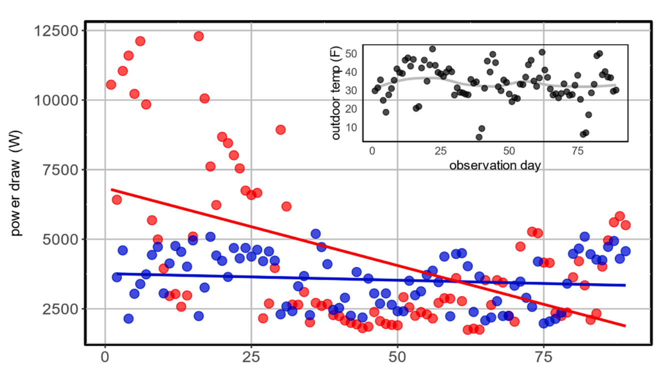

Fig. 5. Power draw of supply air HVAC fans operating in control (-●-) system and intervention system (-●-) in response to HVAC system cleaning in a Boulder, Colorado University classroom and office building. **Inset:** outdoor temperature during observation period.

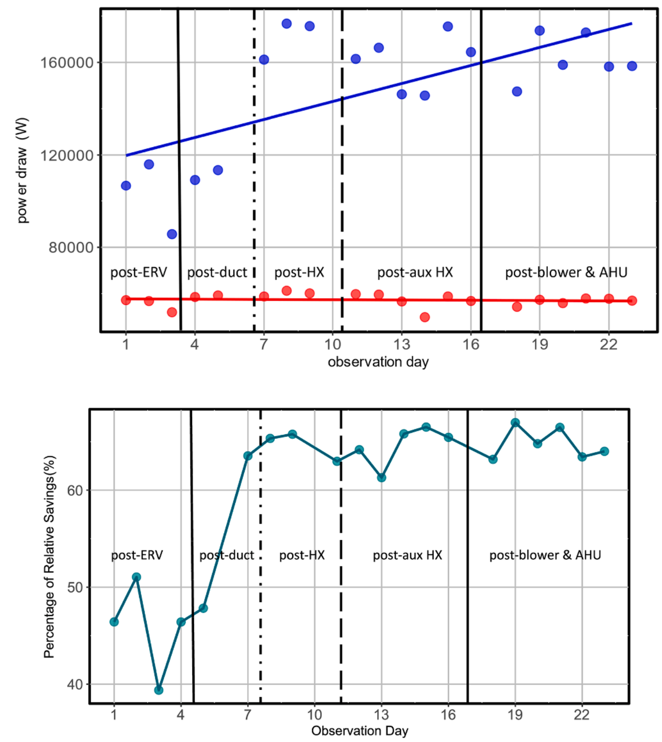

Fig. 6. Top: Power draw of supply air HVAC fans operating in control (-●-) system and intervention system (-●-) in response to stages of HVAC system cleaning in a Pavia, Italy, classroom and office building. **Bottom:** The percentage of relative energy savings over the duration of study.

and self-closing mechanical doors which were shut during these supply air measurements. Measurements were taken on the same days for both control and intervention systems. As shown in Fig. 7, the increase in supply airflow differences generally exhibits a positive slope, indicating the cumulative effect of cleaning on conditioned air flow to the occupied space. In all cases except one, the supply flow differences between control and intervention systems increased over time. Notably, the disparity in supply airflow rates between intervention and control systems rose by over 40 % in Colorado and Italy from pre-cleaning to post-cleaning. The Mississippi site showed a remarkable increase of 174 %.

Initially, the control system at the Mississippi site showed higher pre-cleaning measurements than the intervention system. However, as the cleaning progressed, the intervention measurements surpassed those of the control side. Further examination of the Mississippi site data shows (Fig. 8) that the intervention site had the dirtiest ducts among all the sites, despite having the shortest duct length and the smallest surface area cleaned. Notably, the evaporator coils in Mississippi were in better condition than those at other locations. The positive impact of duct cleaning on supply airflow rates at this site was evident in the data shown in Fig. 7.

In Vermont, both the ducts and coils were relatively clean. The primary issue was the presence of leaves and large debris in the air handling unit (AHU), which was located outside the building on the ground in the open air. An improvement in supply airflow was observed after cleaning the AHU box during the final stages of the cleaning process. This situation might also explain the minimal difference in energy savings between the control and intervention systems at this location, as the main obstruction was large debris rather than dust both in ductwork and cooling/heating equipment.

As judged by conditioned supply airflow, we were able to isolate a clear ventilation performance benefit in response to routine duct cleaning. The greatest change from the previous cleaning phase was an 89 % increase in conditioned supply airflow at the Italian site and 76 %

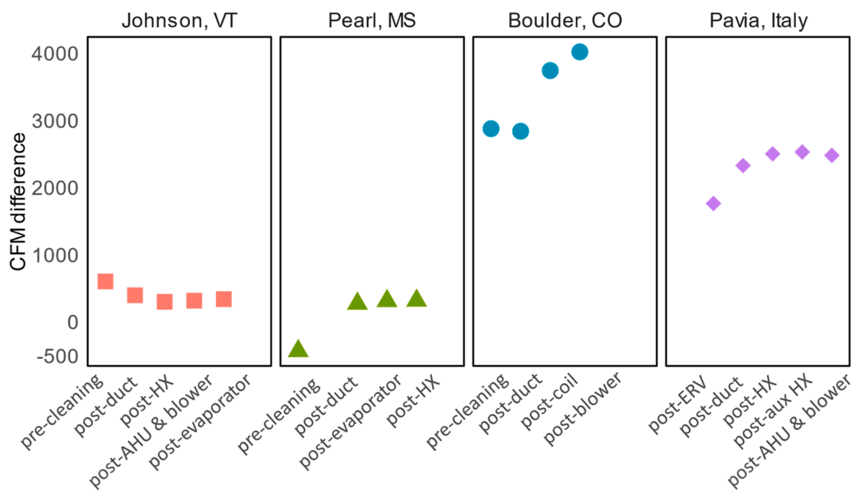

Fig. 7. Difference in supply air flow (ft^3/min) to occupied spaces in response to different cleaning stages at the respective sites: office building, Johnson, VT (■); day care school building, Pearl MS (▲); University classroom building, Boulder, CO (●) and University classroom and office building, Pavia, Italy (◆).

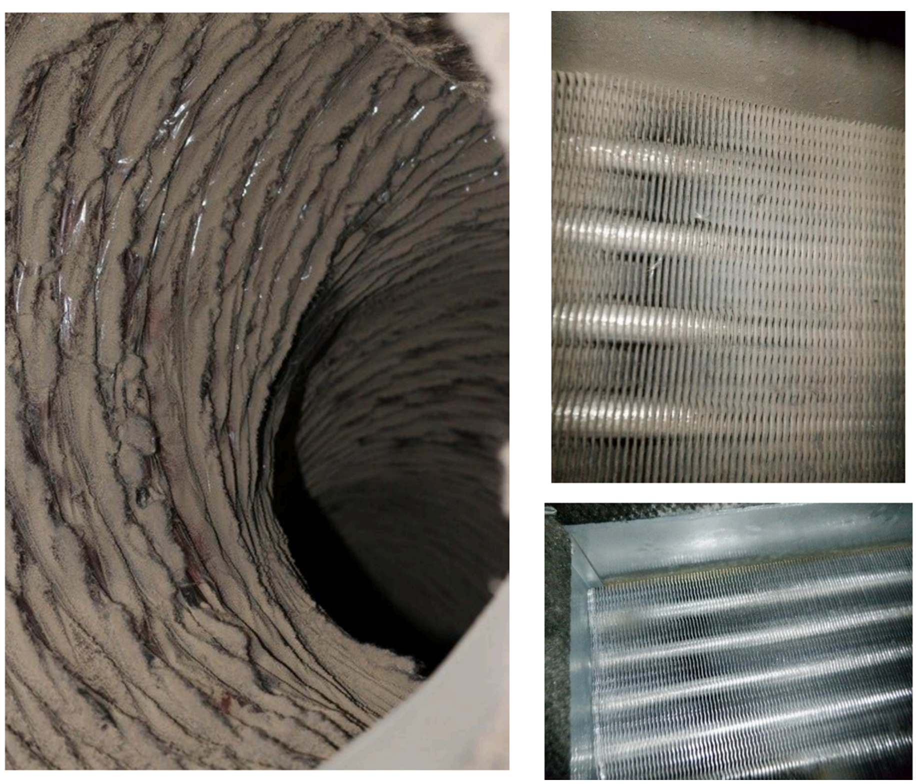

Fig. 8. **Left:** An image of the spiral duct taken before system cleaning at the study location in Pearl, MS. **Right:** A before (top) and after (bottom) system cleaning images of evaporator coils at the study location in Boulder, CO.

in Mississippi, following duct cleaning. In Italy, HVAC coils were not significantly dirty, however the ducts were visibly soiled, notably including large areas of dust accumulation. In Colorado, the most significant effect was observed after coil cleaning, with a 110 % increase in conditioned supply airflow compared to the previous phase, followed by a 20 % increase after blower cleaning. The coils in Colorado were visibly soiled (Fig. 8). Cleaning these coils led a notable increase in supply airflow compared to the control system, highlighting the importance of maintaining clean coils for optimal system performance.

A critical evaluation of conditioned supply airflow measurements shows that airflow rates consistently and significantly increased in cleaned systems compared to their uncleaned counterparts (Eq. (3). Across the different cleaning stages, the average relative increase in supply airflow (CFMs) were as follows: 46 % for the Italian site; 35 % for Colorado site; 19 % for Mississippi site; and 10 % for the Vermont site. Comparative analysis suggests that the larger cleaned duct area, correlates with a greater relative increase in supply airflow. The two sites with the largest improvements, Italy and Colorado, had the greatest duct surface areas cleaned and the highest duct surface-to-serving area ratios. They also had the largest cooling capacities. Details on duct length, duct surface area, area served by the HVAC system, and the cleaned surface-to-served area ratio for each project location are provided in Supplementary Material (A 10).

3.3. Complementary findings on system performance

Our study supports a conclusion that additional (unanticipated) benefits may be associated with HVAC cleaning process. Analysis of the system differential pressure at the Colorado site suggests system stability benefits can result from HVAC cleaning where VAV control is enabled. Fig. 9 illustrates system differential pressure when Variable Air Volume (VAV) boxes were subsequently activated following cleaning intervention; these results suggest improved stability resulted from HVAC cleaning. Notably, the occurrence and range of pressure fluctuations is markedly smaller in the intervention system operation where compared to the control group – a condition which remained apparent for several months after cleaning. This reduction in pressure variability can positively impact system control, particularly considering the influence of (large and capricious) pressure differences on various system components.

It is important to note here that those systems with the longer duct work reaches (Pearl, MS and Pavia, Italy (A-7)), benefited in large supply air flow increases, in response to isolating the duct work cleaning alone.

4. Discussion

Significant energy savings in larger buildings with medium-density occupancy could be realized and verified by implementing the coupled cleaning & monitoring approach described here. Due to differences in system characteristics across the four climatic locations—such as variations in ductwork size and equipment type— direct comparisons of energy savings and supply airflow improvements could not be applied here. However, despite this diversity, net energy consumption significantly decreased during and after HVAC system cleaning, though the degree of impact following each cleaning stage (fans, ducts, heat transfer equipment, etc.) varied by site. Only at one site did the blower energy increase in the intervention system; further analysis indicated that the associated control system was in poor condition, unable to perform adequately in supplying conditioned air at the desired set points.

Our analysis also indicated that larger systems, in terms of ductwork conveyance and cooling capacity, benefited more from cleaning than their smaller counterparts. Examination of all cleaned HVAC systems suggests that a larger cleaned duct area is associated with a greater relative increase in supply airflow. In smaller systems, the larger relative energy benefit is realized from coil cleaning, as cleaner evaporative coils enhance heat exchange efficiency by increasing the effective area for heat transfer. Additionally, clearing the limited flow passage area within coils can further improve flow rates.

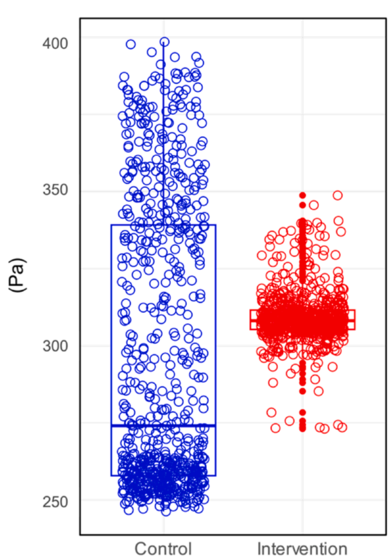

Fig. 9. Distribution of differential pressure (inches water) across filter/cooling coil complex operating in control (-○-) system and intervention system (-○-) in response to HVAC system cleaning in a Boulder, Colorado University classroom and office building with VAV systems engaged. Bottom line of boxes represents 25th percentile; center line of boxes represents 50th percentile; upper line of boxes represents 75th percentile.

Accurate and affordable energy consumption measurements are complex, particularly in larger systems. However, a new generation of IAQ and energy sensors, such as those employed here, now offer affordable detail to energy consumption patterns in response to building hygiene interventions beyond conventional BAS. Additionally, in cases where multiple faults are present within the HVAC system, implementing a maintenance schedule, such as HVAC system cleaning, may offer only potential for system performance diagnosis that was not previously available without on-site inspections [54]. The methods outlined in this study present an advance in leveraging modern monitoring IoT networks for demonstrating the efficacy of HVAC hygiene. Modern energy monitors are accurate and account for energy "losses and gains" in the specific context of short- and long-term seasonal weather changes. Future work can consider extending the post-cleaning data monitoring time to study the re-accumulation of dust (and biofilms) in-and-on HVAC components to better evaluate the longitudinal effects of cleaning.

At this time, we were unable to find a study in scope or design similar to that reported here. To meet rising societal expectations for indoor environment improvements, integrating strategies and analysis for the concomitant management of indoor air quality and maintenance of energy-efficient HVAC systems is essential. In this context, building hygiene costs, notably including periodic HVAC system cleaning, should be weighed in a comprehensive benefits analysis that considers longitudinal energy savings, improved ventilation performance and associated indoor air quality factors.

5. Conclusions

The advent of post-pandemic indoor air quality guidelines suggests that building hygiene will gain increased attention as systematic part of building maintenance portfolios. This study demonstrates how a new generation of affordable IAQ and HVAC system monitors can compile secure IoT archives into an evidence base that enables building mangers to leverage HVAC hygiene into operational scenarios that help optimize energy consumption to help maintain optimal supply airflow rates.

Here we analysed ventilation performance in response to HVAC cleaning in moderately aged buildings (less than 20 years) in four markedly different climates. This study shows that statistically significant improvements in HVAC energy consumption and conditioned air supply can be realized following staged, systematic cleaning of different HVAC systems during the peak of cooling season. On average, intervention systems saved between 41 % and 60 % in conveyance (fan/blower) energy (with one exception) and were able to supply 10 % to 46 % more airflow compared to their uncleaned counterparts. This study demonstrates that the cleaning of HVAC systems can yield significant co-benefits, including enhanced energy efficiency and improved supply airflow rate. These outcomes emphasize the role that facility managers can play in reducing the carbon footprint associated to their building operations. Policies mandating routine, rather than episodic HVAC system maintenance can facilitate the implementation of these measures.

It is important to note that HVAC cleaning can offer additional benefits beyond energy efficiency and fresh air delivery rates. Cleaned HVAC systems presented greater system stability in operational conditions, characterized by decreased fluctuations in system differential pressure. Moreover, the cleaned HVAC systems show decreased dependence on backup equipment, implying possible cost savings in longer-term operational and maintenance expenses.

Maintaining adequately conditioned supply airflow is essential to ensure both comfort and appropriate indoor air quality [55]. We observed the important benefit of significantly increasing conditioned air flow in response to all stages of HVAC cleaning—notably including cleaning the ductwork itself. Lower airflow rates can lead to poor mixing conditions and uneven distribution of conditioned air, resulting in inadequate ventilation and spatial–temporal enthalpy inconsistencies. At the same time, studies have shown that higher airflow rates result in increased fan energy and total annual energy consumption [56]; thus, an optimum balance between minimum air quality considerations, room air mixing regimes and HVAC energy consumption is an important operational goal; indeed, routine HVAC hygiene may help achieve this goal. Only through thoughtful monitoring can such optimization be achieved and confirmed.

CRediT authorship contribution statement

Nasim Ildiri: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Emma Biesiada:** Writing – review & editing, Methodology, Investigation, Data curation. **Tullio Facchinetti:** Writing – review & editing, Visualization. **Norma Anglani:** Writing – review & editing, Visualization, Data curation. **Nouman Ahmed:** Writing – review & editing, Data curation. **Mark Hernandez:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2024.115147.

Data availability

Data will be made available on request.

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