Title
Capturing Energy Savings from Correcting VAV Box Minimums on Campus

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Publication Date
2021-05-01

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Prepared for
UC Berkeley Department of Architecture
May, 2021

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Executive Summary

Improving building energy efficiency is among the many energy challenges that our society faces today. Buildings consume a substantial portion of energy in the United States, accounting for 40% of total energy consumption. One of the most significant contributing factors that cause excessive building energy consumption is inefficient HVAC systems.

This project is funded by The Green Initiative Fund, focusing on improving and supporting UC Berkeley's campus sustainability efforts. This project is also a collaborative effort between the Center for the Built Environment and Facilities Services, including the Energy Office and the Energy Management System group.

The Office of Sustainability at UC Berkeley leads energy and water saving campaigns on campus and has set the goal to reduce energy use intensity by an average of at least 2% annually. One of the proposed energy conservation practices is to improve ventilation efficiency. Our project primarily addresses wasted fan, cooling, and heating energy through excessive air recirculation in campus buildings. By correcting the variable air volume minimum airflow setpoints, we anticipate up to 10-30% HVAC energy savings.

As a pilot project, this report documented how to implement these changes step by step and lower the barrier to entry for Facilities Services to implement this change in other campus buildings.

We developed a comprehensive campus building evaluation matrix and reviewed all 31 campus buildings in the building automation system. We conducted three rounds of analysis, including screening each of the buildings in the building automation system, further reviewing building candidates' case by case, and performing sample zone minimum airflow setpoints calculation. Chavez Student Center was selected as the final building candidate to demonstrate the energy savings measure. In the end, the total minimum airflow rate savings at Chavez Student Center is 4,615 cfm based on the calculation.

Since this study was conducted in the middle of the pandemic, the COVID had put many restrictions on this project. The first limitation was the difficulty of finding buildings with meters appropriate for us to measure savings. Meters are either not functional, or broken, or installed incorrectly, or do not connect to the building management system. The on-site occupancy investigation was also affected by building closure. Because the campus modified its ventilation strategies in response to the California Department of Public Health's COVID-19 Industry Guidance for Institutions of Higher Education, the recirculation damper in the air handling unit in Chavez Student Center is fully closed. As a result, this will impact the fan power savings estimation from correcting the minimum airflow rate setpoints. The results of this study will not indicate a normal operation mode in the building.

1. Introduction

Improving building energy efficiency is one of the most demanding challenges that our society faces today. Buildings consume 40% of total energy consumption in the United States, with 21% from the residential sector and 18% from the commercial sector. Figure 1 shows the share of total U.S. energy consumption by end-use sectors in 2019 [1]. For commercial buildings, electricity and natural gas are the most common energy sources [2]. Lighting, refrigeration, ventilation, and cooling are the top four primary end uses of electricity for commercial buildings, as shown in Figure 2 [2]. Education was the third in the top five energy-consuming commercial building categories, which used 10% of the energy consumed by all commercial buildings in 2012 according to the U.S Energy Information Administration [2].

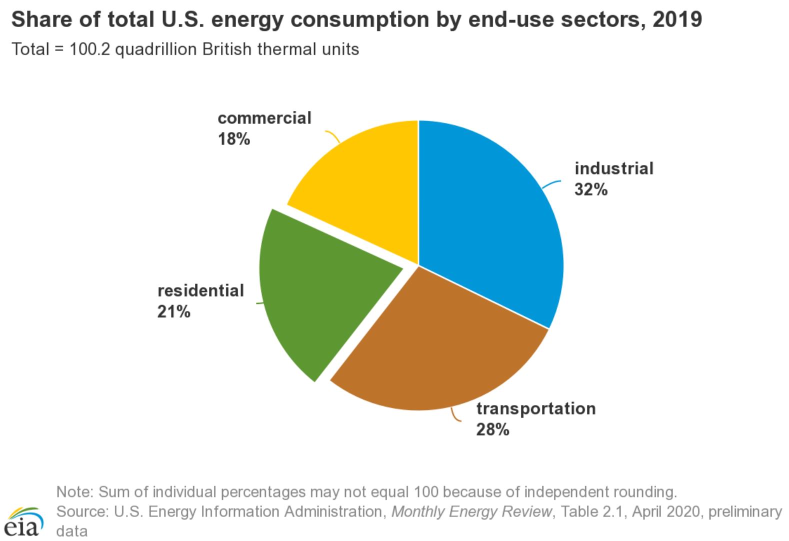

Figure 1: Energy consumption by ends in U.S

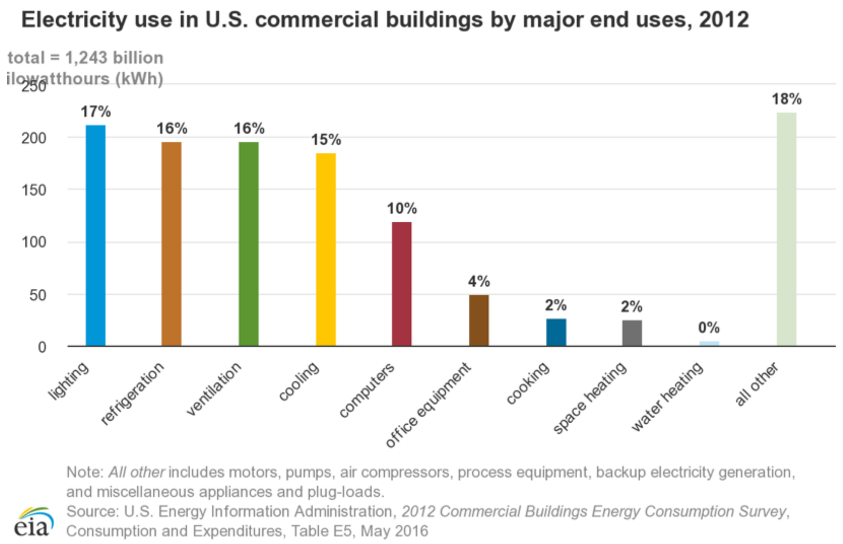

Figure 2: Electricity consumption by ends in U.S commercial buildings

The Office of Sustainability at the University of California, Berkeley (UC Berkeley) has a mission to: "achieve carbon neutrality and zero waste with a focus on renewable energy, resource saving and stewardship, greening the built environs, and inspiring resilient and inclusive institutional change [3]". The campus has set the goal to reduce energy use intensity (EUI) by an average of at least 2% annually [4]. In November 2020, UC Berkeley also updated its policy on energy use to outline new energy conservation practices, including a specific framework to improve ventilation efficiency. The campus recommended using variable air volume (VAV) systems since the building controls should have the load-tracking ability, and ventilation rates can be reduced during light occupancy (demand ventilation) [4]. The cogeneration plant provides approximately 90% of the electricity and 100% of the steam needs for the campus [5]. However, as it is aging, the campus has initiated many studies to explore the opportunities to improve the energy delivery system and alternative fuel sources for the main campus [6].

This project is funded by The Green Initiative Fund (TGIF). TGIF is UC Berkeley's campus green fund, and it provides funding for projects that improve and support UC Berkeley's campus sustainability efforts [7]. This project is also a collaborative effort between the Center for the Built Environment (CBE) and Facilities Services, including the Energy Office and the Energy Management System (EMS) group.

Both the CBE and the Energy Office focus on supporting carbon neutrality at Cal by reducing energy consumption and improving energy efficiency. This project will move the campus towards these goals by reducing campus energy waste and the associated emissions.

2. Background

Variable Air Volume (VAV) systems are one of the most common Heating, Ventilation, and Air Conditioning (HVAC) systems for commercial and institutional buildings in the US. The typical design and control strategies for these systems are quite inefficient, especially in older buildings. One specific practice that has resulted in significant energy waste in building ventilation systems is setting a high minimum airflow setpoint for each zone (30-50% of maximum airflow) [8]. Excessive air recirculation wastes substantial fan, cooling, and heating energy (and therefore it increases GHG emissions).

Designers have traditionally followed this practice because of concerns that VAV systems would struggle to control precisely at low airflow due to the non-linearity of dampers and that lower airflow might cause cold drafts to occupants. In reality, high minimum airflow often causes over-cooling in spaces. Researchers from CBE and others have shown each of these previous assumptions to be unwarranted, and that lower minimums are desirable both for energy and thermal comfort [8]. To demonstrate this, CBE corrected the minimums in almost 1 million square feet of office buildings in the Bay Area and measured between 10-30% HVAC energy savings while measurably improving thermal comfort at the same time [9]. This project lead to changes in both the California building code and national energy standards, requiring reduced minimum airflow for all new buildings.

However, most existing buildings – including a significant proportion of campus buildings - do not meet this new code requirement. It is critically important to note that reducing VAV box minimum airflow rates does not reduce the amount of fresh outdoor air entering the building. Instead, it reduces the amount of air that is unnecessarily recirculating throughout the building's HVAC system (see Figure 3 below).

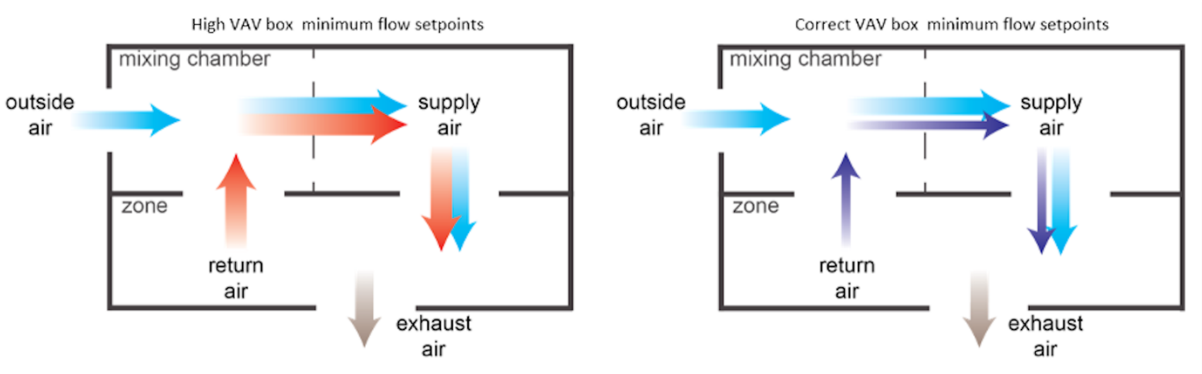

Figure 3: High vs correct VAV box minimum flow setpoints

3. Purpose and Objectives

The project's overall goals are to provide a quantitative energy-saving result for at least one campus building and write a detailed, publicly available guide on the implementation process.

Our project primarily addresses the issue of wasted fan, cooling, and heating energy in campus buildings. Reducing this waste will contribute to energy goals identified in UC Berkeley's 2025 Carbon Neutrality Planning Framework: energy use reduction through building level energy efficiency projects [10]. Energy is wasted through excessive air recirculation, and by correcting the VAV minimum flow rates, we anticipate up to 10-30% HVAC energy savings.

Although savings will be significant, the initial research and preparation needed for this project will require a significant time investment that is impossible with existing staff. We will complete the initial lift required to jumpstart these updates to campus buildings' controls through this project. This project and its legacy will help the campus meet Carbon Neutrality and Building Energy Use reduction goals. These minimum flow rates are now required by building code in new buildings. However, there are no requirements for Berkeley to implement these flow rates in existing buildings.

As a pilot project, we reviewed existing campus buildings and selected the best building to demonstrate this energy savings measure. As part of the report, we will project the savings across all campus buildings. We believe it is very likely that the energy cost savings will be sufficient to pay back the costs of implementing this measure within three years or less. Thus, the project can continue after the end of the grant period – i.e., led by the EMS group, the Energy office, or future students. This report will document how to implement this measure and lower the barrier to entry for Facilities Services to implement this change in other campus buildings and for other organizations to implement this change in their buildings anywhere in the world.

4. Methods

4.1. Energy Management System

The study started with understanding how the campus buildings are controlled. The EMS group in the Facilities Service department uses building automation systems to control and monitor more than 75 campus buildings [11]. The EMS group is currently transitioning its automation systems from outdated Barrington systems to Automated Logic (ALC) systems. Almost 31 campus buildings have connected to the ALC so far. The figure below shows the interface for UC Berkeley's ALC system.

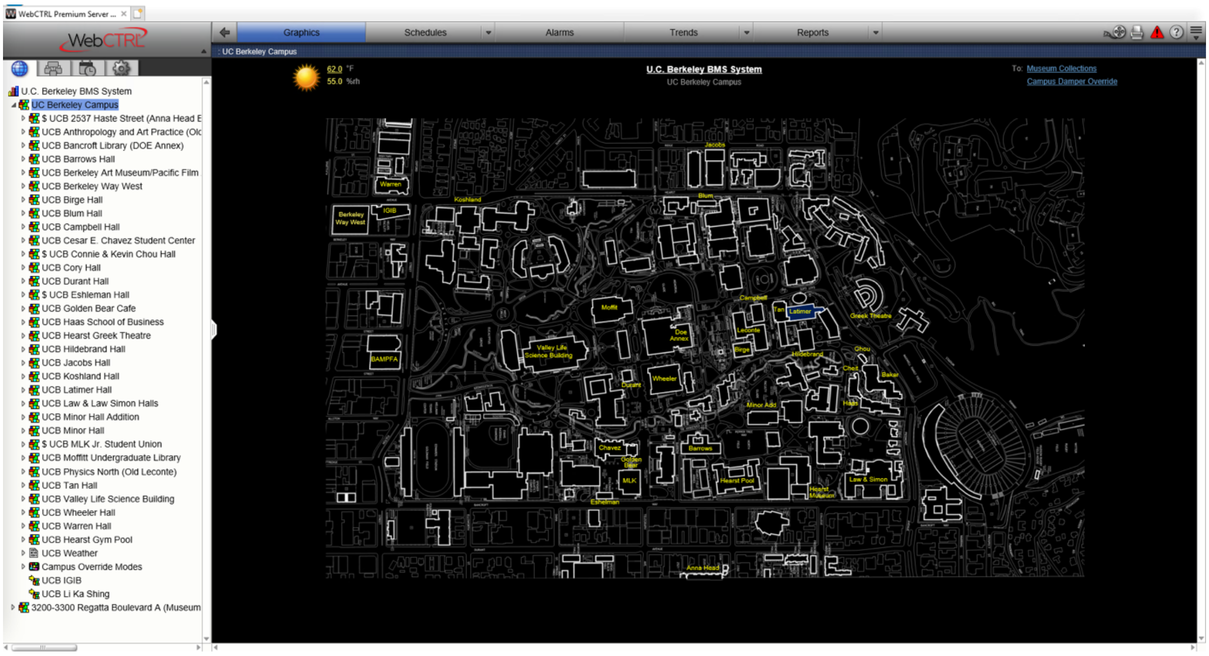

Figure 4: The ALC system interface of UC Berkeley

The modern ALC system provides much more detailed trending data than other older building automation systems on campus, especially on the building level scale. For example, researchers and students can access an air handling unit for a specific building and view trend data for supply air rate. Most of the data are collected through various built-in sensors in the HVAC system. Those data were then uploaded to the EMS through Building Automation and Control (BAC) networks. BACnet is a communication protocol designed to provide mechanisms for computerized building automation devices to exchange information. The figure below shows the example of a building-level ALC interface for Durant Hall with heat pump trend data.

Figure 5: The building level ALC interface with trending data example

4.2. Campus Building VAV Evaluation Matrix

The second step for this study was to develop a comprehensive campus building evaluation matrix. The matrix can assist us with determining the best building candidates that are flexible enough to allow us to update VAV minimum airflow setpoints.

The campus building VAV evaluation matrix includes basic building information features such as built year, area, and stories. It also includes VAV system characteristics such as VAV box distribution, number of VAV units, and VAV box types. Moreover, the matrix contains HVAC type, which mainly focuses on the components within the ventilation system that connect to the VAV units in the building. Metering is another critical feature that was included in the matrix. More detail about how metering issues would impact this study are discussed in the "Discussion and Limitations" section.

All 31 campus buildings in the ALC are evaluated based on the following evaluation matrix:

FEATURE	EXPLANATION
VAV Box Availability	• A binary feature that describes whether the building has VAV boxes for ventilation or not.
Built Year	• The official built year for a building. • If the building had undergone a major renovation or the HVAC system had been upgraded, the built year would be when the renovation was completed.
Area (ft^2)	• The floor area of a building. • If the building in the ALC system only represents part of the building, the area will only count the space shown in the ALC system.
Stories	• This feature specifies the number of floors, roof, ground floor, basement, and other types of building stories.
VAV Box Distribution	• This feature specifies the story number, which has VAV box units in a building.
Number of VAV Units	• This feature listed the total number of VAV units within a building.

VAV Box Types	• The type of a VAV box comes from the description within the Logic Panel in the ALC system. General VAV box types in the campus ALC includes: • VAV with cooling only: typically serve interior zones • VAV with Hot water reheat • VAV with fan powered: typically serve enclosed spaces such as conference room • VAV with CO2 control • VAV with window switch • VAV with occupancy control • VAV with humidity control
HVAC Type	• This feature mainly focuses on the components within the ventilation system that connect to the VAV units in the building, such as air handling units (AHU) or rooftop units (RTU).
Hot Water Meter	• A binary feature that describes whether the building has a hot water meter that measures hot water flow, supply and return temperature.
BTU Meter	• A binary feature that describes whether the building has a BTU meter that measures steam flow or energy usage.

Table 1: Campus building VAV Evaluation Matrix

4.3. Analysis of 31 Campus Buildings

The next step for this study was to apply the above campus building VAV evaluation matrix to the 31 buildings in the ALC system. We performed multiple rounds of analysis to review existing campus buildings until we selected the best building candidates to demonstrate this energy savings measure.

4.3.1 First Round of Analysis – Screening All 31 Campus Buildings in the ALC

In the first round of analysis, we screened each one of the buildings in the ALC system. The primary goal was to determine whether the building has VAV systems installed or not. The results are shown in the following Table 2.

Building Name	VAV Box Availability	Built Year	Area (ft²)	Stories	VAV Box Distribution	Number of VAV Units	VAV Box Types	HVAC Type	Hot Water Meter	BTU Meter	Notes
Anna Head Bldg E/F	No										
Barrows Hall	No										
Berkeley Art Museum/ Pacific Film Archive	Yes	2016	83,000	3 floors with roof and 1 lower level	Floor 1; Roof	26	Cooling HW Reheat Humidity CO2 Control	AHU with CHW, HW, Econ, CO2, CFM, and Dehu	Yes	Yes	21 normal VAV units with 5 Exhaust Ventilation VAV boxes
Berkeley Way West	Yes	2018	230,000	9 floors	Only Floor 1 has VAV	35	Cooling HW Reheat CO2 Control Fan Powered	OA from IDECs (Indirect Evaporative Cooler) to AHU with CHW, HW, Econ, CFM, and Dehu	Yes	Yes	Most of the space use UFT (Underfloor Fan Terminal) to provide ventilation
Birge Hall	No										
Blum Hall	No										
Campbell Hall	Yes	2014	85,000	6 floors with roof and 1 lower level	Floor 1; Floor 2; Floor 3; Floor 4; Floor 5; Floor 6;	28	Cooling HW Reheat	AHU with CHW, HW, Econ, CO2, CFM, and Dehu	N/A	Yes	This building serves as a model of sustainability for the campus; strategies for energy reduction, thermal heat gain mitigation, and natural ventilation are fully integrated into the design.
Cesar E. Chavez Student Center	Yes	Built 1960. Renovated 1990.	N/A	2 floors with roof and basement	Basement; Floor 1; Floor 2	59	Cooling HW Reheat	AAON AC unit with Econ and HW; AHU with Econ and HW	N/A	N/A	
Connie & Kevin Chou Hall	Yes	2017	80,000	6 floors with roof and basement	Floor 1; Floor 2; Floor 3; Floor 4; Floor 5; Floor 6;	46	Cooling Active Chilled Beam Window Switch HW Reheat CO2 Control	AHU1: CHW (Low temp system + medium temp system + chilled beam loop + CW system) and HW AHU2: RTU with HW	Yes	Yes	Hybrid system of VAV and ACB for all VAV units except floor 6

Bancroft Library	Yes	Built 1949. Reopened in 2009 after renovation.	130,000 or 75,000 of surface space assigned for library purpose	5 floors with Penthouse Equipment and basement	Basement; Floor 1; Floor 2; Floor 3; Floor 4; Floor 5	102	Cooling HW Reheat Neutral Humidification CO2 Min Airflow Reset	AHU with cooling duct (consist of CW and HW) and neutral duct	N/A	N/A	
Durant Hall	No										
Eshleman Hall	No										
Golden Bear Café	No										The Golden Bear Café use wall mounted ductless HVAC units
Cheit Hall	Yes	1995	N/A	4 floors	Floor 1; Floor 2; Floor 3; Floor 4;	26	Cooling HW Reheat	2 AHUs with CH and Econ	N/A	N/A	Mixed use of VAV and CAV
Hearst Greek Theatre	Yes	Built 1903. Reopened in 2012 after renovation.	N/A	Roof, ground floor, and basement	Basement; Ground floor;	15	Cooling CO2 Control	1 AHU with Econ and Steam Heating,	No	No	
Hildebrand Hall	No										
Jacobs Hall	Yes	2015	24,000	3 floors with basement	Basement; Floor 1; Floor 2; Floor 3;	7	Cooling HW Reheat CO2 Control	1 AHU with CHW, CO2, and CFM	Yes	Yes	
Koshland Hall	No										
Kroeber Hall Hearst Museum Gallery	Yes	1959	N/A	1 floor with roof	Floor 1	1	Cooling	1 RTU with HW, Dehumidification Control, and Humidification Control	N/A	N/A	
Latimer Hall	No										
Law & Law Simon Halls	Yes	Built 1966. Reopened in 2012 after renovation.	N/A	5 floors with roof, ground floor, and 2 south lower levels	Only the South Pavilion has VAV box; South Lower Level LL1; South Lower Level LL2	23	Cooling HW Reheat CO2 Control External Actuator Fan Powered	1 AHU with Econ, CHW, and Domestic Hot Water system (DHW)	Yes	Yes	Expanded the law library into an underground facility under a new South Pavilion.
Leconte Hall	No										

Minor Hall Addition	Yes	1978	N/A	5 floors with roof	Floor 1; Floor 2; Floor 3; Floor 4; Floor 5;	82	Cooling HW Reheat CO2 Control	4 AHUs with CHW, Econ, and HW	N/A	Yes	
MLK Jr. Student Union	Yes	Built 1961. Reopened in 2015 after renovation.	N/A	5 floors with basement	Basement; Floor 1: Floor 2	82	Cooling HW Reheat CO2 Control	1 AHU with Econ, CHW, and HW	Yes	Yes	
Moffitt Undergraduate Library	Yes	Built 1970. Reopened in 2016 after renovated floors 4 and floor 5.	38,000 for Floor 4 and Floor 5	ALC only has data for floor 4, floor 5, and basement	Floor 4; Floor 5	41	Cooling HW Reheat Fan Powered CO2 Control	2 AHUs with CH, Econ, and HW	N/A	Yes	
Tan Hall	No										
Valley Life Science Building	No										
Wheeler Hall	Yes	Built 1917. Reopened in 2017 after renovation.	137,000	4 floors with roof, basement, and sub-basement	The auditorium at Floor 3 uses VAV boxes. Sub-basement also uses VAV boxes.	6	Cooling Only	2 AHUs with HW	Yes	Yes	Most spaces use radiant heating.
Warren Hall	No										
Innovative Genomics Institute Building (IGIB)	Yes	2017	N/A	5 floors with roof and basement	This project only focusses on VAV box in the office zones. Floor 1; Floor 2; Floor 3; Floor 4; Floor 5;	86	Cooling HW Reheat Occupancy & Window Switches Control CO2 Control	1 AHU with HW, CHW, Econ, and Electronic Filter	Yes	Yes	Each floor is divided into lab zones and office zones. All lab zones use supply only lab VAV boxes, which are excluded from this project.
Li Ka-Shing Center	Yes	2011	200,000	5 floors with roof and basement	Basement; Floor 1; Floor 2; Floor 3; Floor 4; Floor 5;	> 200	Cooling HW Reheat Occupancy Control CO2 Control		Yes	N/A	Each floor has a mixture of different types of VAV: 1. Common VAV with modulating reheat valve and return air damper 2. Common VAV with fume hood status, modulating reheat valve, and return air damper 3. Return air valve or exhaust air valve only terminal box

Table 2: First round of analysis – Summary of 31 buildings in the ALC

From Table 2, we observed that not every building in the ALC system has VAV boxes installed. Furthermore, there is a significant difference for the built year, spanning from the year 1903 for the Hearst Greek Theatre to the year 2018 for the Berkeley Way West. However, only considering the built year as a feature sometimes will not accurately reflect the actual condition and the energy saving potentials if we update the VAV minimum airflow setpoints for the building. As a result, we also considered the year of major renovations or system upgrades to assist our decision-making process.

On the other hand, VAV units are not evenly distributed across each story for some buildings. For example, for the Berkeley Way West, only floor 1 has VAV units, while most of the space uses underfloor air distribution (UFAD) and underfloor fan terminals to provide ventilation and air conditioning. So, for this study, the building cannot be selected as the candidate to demonstrate the energy savings measure.

4.3.2 Second Round of Analysis – Building Candidates with High Energy Saving Potentials

17 out of the 31 buildings in the ALC system have VAV boxes for ventilation. In the second round of analysis, we evaluated the remaining 17 buildings by comparing the following features:

1. Number of VAV Units
2. VAV Box Distribution

To ensure high energy saving potentials of the candidate buildings, we set the minimum number of VAV units in the building as 25. As a result, 6 buildings were eliminated from the list as shown below:

1. **Kroeber Hall Hearst Museum Gallery:** 1 VAV unit
2. **Wheeler Hall:** 6 VAV units
3. **Jacobs Hall:** 7 VAV units
4. **Hearst Greek Theatre:** 15 VAV units
5. **Berkeley Art Museum/ Pacific Film Archive:** 21 regular VAV units with 5 Exhaust Ventilation VAV boxes
6. **Law & Law Simon Halls:** 23 VAV units

For the remaining 11 buildings, after further reviewing each one of them, we eliminated 4 buildings due to the following reasons:

1. **Berkeley Way West:** This is a relatively new building, which was built in 2018. The most concerning issue about this building is that only one floor uses VAV boxes as the primary ventilation strategy. Most of the spaces, other eight floors, use UFAD to provide ventilation. Due to the unbalanced VAV box distribution and the use of UFT as the primary ventilation approach, this building is inappropriate to be considered the best candidate for this project.
2. **Connie & Kevin Chou Hall:** This is also a relatively new building, which was built in 2017. The building's primary concern is using a hybrid ventilation system of VAV and Active Chilled Beam (ACB) for all VAV units on floor 1 to floor 5. According to

the article, *VAV Reheat Versus Active Chilled Beams & DOAS* published in ASHRAE Journal, May 2013 [12], chilled beams allow a significant reduction in the primary airflow rates, especially in low density perimeter zones. Due to the dominated use of the hybrid system of VAV and ACB, this building is inappropriate to be considered the best candidate for this project as the hybrid system may not objectively reflect the performance of the VAV system itself in the field study.

3. **Innovative Genomics Institute Building:** This is another relatively new building, which was built in 2017. Each floor is divided into lab zones and office zones. All lab zones use supply only lab VAV boxes. Due to the highly mixed lab zones and office zones, this building is inappropriate to be considered the best candidate for this project. The sophisticated ventilation control strategy and the laboratory purpose building type may not represent the regular VAV operation.
4. **Li Ka- Shing Center:** This building was built in 2011. The Li Ka-Shing Center consists of highly specialized facilities for cutting edge instrumentation and containment areas for handling viruses, teaching suites composed of a conference room and lecture theatre, and flexible laboratories [13]. The building has a mixture of different types of VAV for each floor, including return air valve or exhaust air valve only terminal box and VAV with fume hood control. Due to the highly mixed lab zones and office zones and dedicated ventilation strategies for the specialized facilities, this building is inappropriate for the best candidate for this project as the building type may not represent the regular VAV operation.

Table 3 below shows the summary of the 7 building candidates which have high energy saving potentials.

Building Ranking	Building Name	VAV Box Availability	Built Year	Built Year Note	Area (ft²)	Stories	VAV Box Distribution	Number of VAV Units	VAV Box Control Logic	VAV Box Types	HVAC Type	Hot Water Meter	BTU Meter
1	Minor Hall Addition	Yes	1978	Minor Hall Addition had VAV and Controls retrofied in 2016 with Taylor Engineering	N/A	5 floors with roof	Floor 1; Floor 2; Floor 3; Floor 4; Floor 5;	82		Cooling HW Reheat CO2 Control	4 AHUs with CHW, Econ, and HW	N/A	Yes
2	Cesar E. Chavez Student Center	Yes	1990	Built 1960. Renovated 1990.	N/A	2 floors with roof and basement	Basement; Floor 1; Floor 2	59		Cooling HW Reheat	AAON AC unit with Econ and HW; AHU with Econ and HW	N/A	N/A
3	Cheit Hall	Yes	1995	Cheit Hall had Cooling and Energy retrofit in 2013 with AIRCO.	N/A	4 floors	Floor 1; Floor 2; Floor 3; Floor 4;	26		Cooling HW Reheat	2 AHUs with CH and Econ; Mixed use of VAV and CAV	N/A	N/A
4	Bancroft Library	Yes	2009	Built 1949. Reopened in 2009 after renovation.	130,000 or 75,000 of surface space assigned for library purpose	5 floors with Penthouse Equiment and basement	Basement; Floor 1; Floor 2; Floor 3; Floor 4; Floor 5	102	The VAV Box control logic has discharge air temperature sensor and has both cooling max and heating max airflow setpoint. As a result, this is a Dual Maximum VAV Box Logic	Cooling HW Reheat Neutral Humidification CO2 Min Airflow Reset	AHU with cooling duct (consist of CW and HW) and neutral duct (consist of stm)	N/A	N/A
5	Campbell Hall	Yes	2014		85,000	6 floors with roof and 1 lower level	Floor 1; Floor 2; Floor 3; Floor 4; Floor 5; Floor 6;	28		Cooling HW Reheat	AHU with CHW, HW, Econ, CO2, CFM, and Dehu	N/A	Yes
6	MLK Jr. Student Union	Yes	2015	Built 1961. Reopened in 2015 after renovation.	N/A	5 floors with basement	Basement; Floor 1;Floor 2	82		Cooling HW Reheat CO2 Control	1 AHU with Econ, CHW, and HW	Yes	Yes
7	Moffitt Undergraduate Library	Yes	2016	Built 1970. Reopened in 2016 after renovated floors 4 and floor 5.	38,000 0 for Floor 4 and Floor 5	ALC only has data for floor 4, floor 5, and basement	Floor 4; Floor 5	41		Cooling HW Reheat Fan Powered CO2 Control	2 AHUs with CH, Econ, and HW	N/A	Yes

Table 3: Second round of analysis – Building candidates with high energy saving potentials

4.3.3 Third Round of Analysis – Sample Zone Minimum Airflow Setpoints Calculation

The next step of the analysis was to perform sample zone minimum airflow setpoints calculation for the above 7 building candidates. We selected 5% - 10% of the zones within each building and compared the design ventilation minimum airflow setpoints with the current VAV configuration. The results informed us which building should be selected as the final candidate to demonstrate the energy savings measure.

The ventilation minimum airflow is the larger value of 0.15 cfm per square feet or 15 cfm per person based on *Section 120.1 – Requirements for Ventilation and Indoor Air Quality* in the *2019 California Title 24* [14]. The occupancy density is estimated from *Table 6-1 Minimum Ventilation Rates in Breathing Zone* in the *ASHRAE 62.1 -2019 Ventilation for Acceptable Indoor Air Quality* when the actual occupant density is unknown [15].

After requesting permission to log into the Facilities Services' Record Archives in the Box, we could access the mechanical zone level floor plans for different campus buildings. Those mechanical plans provide relative information about the ductwork and diffusers. As a result, we could trace the downstream of the VAV box and calculate the serving area for each VAV unit. Some campus building archives contain room type information, which can be used to determine the occupancy number. However, the room type information may be outdated, and we suggested performing an on-site occupancy investigation if possible.

A step-by-step minimum airflow rates calculation will be provided in section 4.4.

Zone Number	**Floor Area (ft²)**	**Occupancy**	**Ventilation Min Airflow (cfm)**		**Design Ventilation Min Airflow (cfm)**	**Current VAV Configuration (cfm)**	**% Difference from Design Ventilation Min Airflow**
			Area	**Occupancy**			
VR 1201	134	1	20	15	20	75	275%
VR 1202	495	6	74	90	90	105	17%
VR 1101	629	8	94	120	120	140	17%
VR 2303	1000	8	150	120	150	225	50%

Table 4: Minor Hall Addition sample zone minimum airflow setpoints calculation

For the Minor Hall Addition, VAV units information came from 12425I-Minor Hall Addition Addendum 4 Set – Mechanical [16]. Minor Hall Addition had VAV system and controls retrofitted in 2016 by Taylor Engineering. The 12425I file has minimum airflow rate calculation with respect to area and occupancy. We verified that the minimum airflow rates for the area in the document met the Title 24 ventilation requirement (0.15 cfm/ft²) after cross-checking.

Zone Number	**Floor Area (ft²)**	**Occupancy**	**Ventilation Min Airflow (cfm)**		**Design Ventilation Min Airflow (cfm)**	**Current VAV Configuration cfm)**	**% Difference from Design Ventilation Min Airflow**
			Area	**Occupancy**			

VR 3-2	255	2	38	30	38	50	31%
VR 3-14	184	1	28	15	28	30	9%
VR 3-15	184	1	28	15	28	30	9%
VR 3-16	279	2	42	30	42	120	187%
VR 3-17	1269	6	190	90	190	200	5%
VR 3-20	322	3	48	45	48	50	3%

Table 5: Cesar E. Chavez Student Center sample zone minimum airflow setpoints calculation

For the Cesar E. Chavez Student Center, VAV units information came from Lower Sproul Redevelopment Project Bid Package 5- Volume 4 [17].

Zone Number	Floor Area (ft^2)	Occupancy	Ventilation Min Airflow (cfm)		Design Ventilation Min Airflow (cfm)	Current VAV Configuration (cfm)	% Difference from Design Ventilation Min Airflow
			Area	Occupancy			
VAV 1-1	1151	60	173	900	900	300	-67%
VAV 1-2	287	10	43	150	150	Cannot communicate with controller in the ALC	
VAV 1-3	1164	60	175	900	900	775	-14%
VAV 4-2	244	2	37	30	37	50	36%

Table 6: Cheit Hall sample zone minimum airflow setpoints calculation

For the Cheit Hall, VAV units information came from Haas School of Business – CAAN 1234 – Cheit Hall and Baker Facility HVAC [18]. Cheit Hall was retrofitted in 2013 by AIRCO. During that time, Cheit Hall installed new VAV boxes and upgraded its digital controls. Compared to the current VAV configuration, the larger calculated airflow value may cause by overestimation of the occupancy density.

Zone Number	Floor Area (ft^2)	Occupancy	Ventilation Min Airflow (cfm)		Design Ventilation Min Airflow (cfm)	Current VAV Configuration (cfm)	% Difference from Design Ventilation Min Airflow
			Area	Occupancy			
VAV C-2-1	348	4	52	60	60	500	733%
VAV C-2-4	940	8	141	120	141	500	255%
VAV B-2-01	1660	17	249	255	255	300	18%
VAV C-2-8	720	4	108	60	108	75	-31%
VAV C-2-14	253	3	38	45	45	30	-33%
VAV C-2-13	255	3	38	45	45	30	-33%
VAV C-2-17	519	6	78	90	90	90	0%
VAV B-3-03	1596	16	239	240	240	540	125%

Table 7: Bancroft Library (DOE Annex) sample zone minimum airflow setpoints calculation

For the Bancroft Library (DOE Annex), we cannot access the mechanical zone level floor plans that show the ductwork and VAV units. As a result, we used the colored VAV zones in the ALC system to calculate the area, as shown below.

Figure 6: Bancroft Library VAV zone demo

Zone Number	Floor Area (ft²)	Occupancy	Ventilation Min Airflow (cfm)		Design Ventilation Min Airflow (cfm)	Current VAV Configuration (cfm)	% Difference from Design Ventilation Min Airflow
			Area	Occupancy			
VAV-104	813	9	122	135	135	140	4%
VAV-102	731	37	110	555	555	300	-46%
VAV-205	987	20	148	300	300	110	-63%
VAV-303	1103	6	165	90	165	60	-64%

Table 8: Campbell Hall sample zone minimum airflow setpoints calculation

For the Campbell Hall, VAV units information came from 12017A- 2015-07-01 Mech PDF Record Drawing [19]. The document has minimum airflow rate calculations, but the number is not clear regarding pulling from area or occupancy. More than 90% of the current VAV minimum airflow configurations in the ALC are consistent with the minimum airflow rates in the document. Compared to the current VAV configuration, the larger calculated airflow value may cause by overestimation of the occupancy density.

Zone Number	Floor Area (ft²)	Occupancy	Ventilation Min Airflow (cfm)		Design Ventilation Min Airflow (cfm)	Current VAV Configuration (cfm)	% Difference from Design Ventilation Min Airflow
			Area	Occupancy			
VAV-1.06	1601	112	240	1680	1680	2400	43%
VAV-1.19	684	10	103	154	154	120	-22%
VAV-1.20	731.5	11	110	165	165	235	43%
VAV-1.21	1250	19	188	281	281	310	10%
VAV-1.29	1911.4	19	287	285	287	550	92%
VAV-1.27	485	8	73	120	120	160	33%

Table 9: MLK Jr. Student Union sample zone minimum airflow setpoints calculation

For the MLK Jr. Student Union, we cannot access the mechanical zone level floor plans that show the ductwork and VAV units. As a result, we used the colored VAV zones in the ALC system to calculate the area, as shown below.

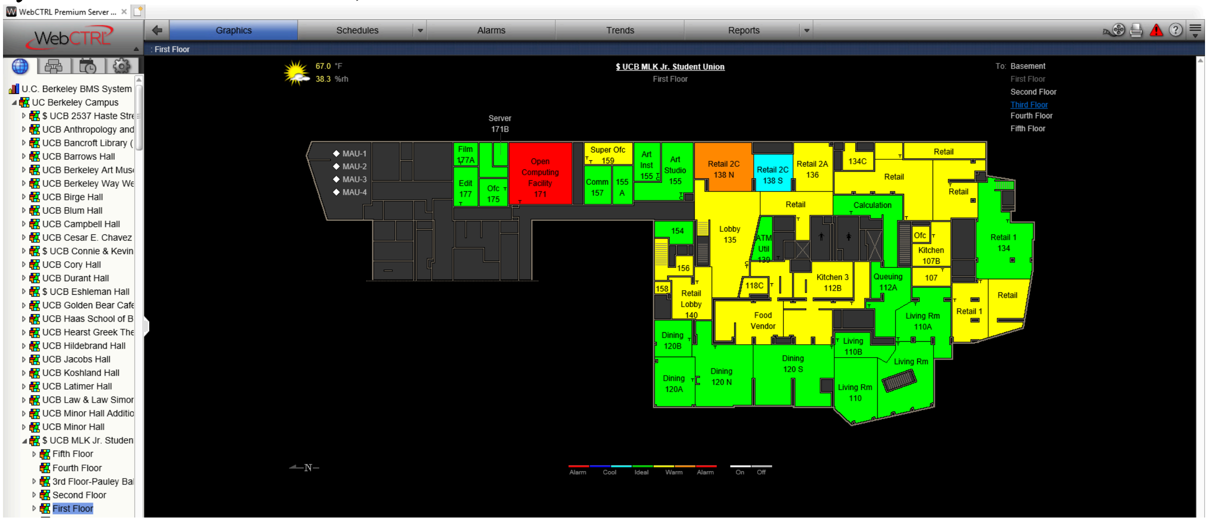

Figure 7: MLK Jr. Student Union VAV zone demo

For the Moffitt Undergraduate Library, VAV units information came from 12643A – Moffit 4th and 5th Floor and Roof Renovations – 180104_UCB Moffitt Record Set [20]. Moffitt Library had VAV systems retrofitted on 4th and 5th floor by Taylor Engineering. The Record Set has detailed minimum airflow rate calculations regarding area and occupancy. We verified that both the area basis and occupancy basis minimum airflow rate calculation met the ventilation requirement set by California Title 24 (0.15 cfm/ft^2 or 15 cfm/person). However, both the design minimum airflow rates shown in the document and the active setpoints in the ALC system are not equal to the larger number of area basis or occupancy basis minimum airflow rate.

4.4. Update VAV Minimums for Chavez Student Center

After comparing the above 7 building candidates, we selected the Chavez Student Center to demonstrate the energy savings measure. In this section, we will demonstrate a step-by-step VAV minimum airflow setpoint calculation for one VAV unit. We will use unit VC 2-7a as an example.

4.4.1 Locate VAV Unit and Corresponding Serving Zones

The first step was to review the Lower Sproul Redevelopment Project Bid Package 5-Volume 4 [17] from the Facilities Services' record archives in the Box. Then, we found the HVAC plan with ductwork and VAV units, as shown in the following figure.

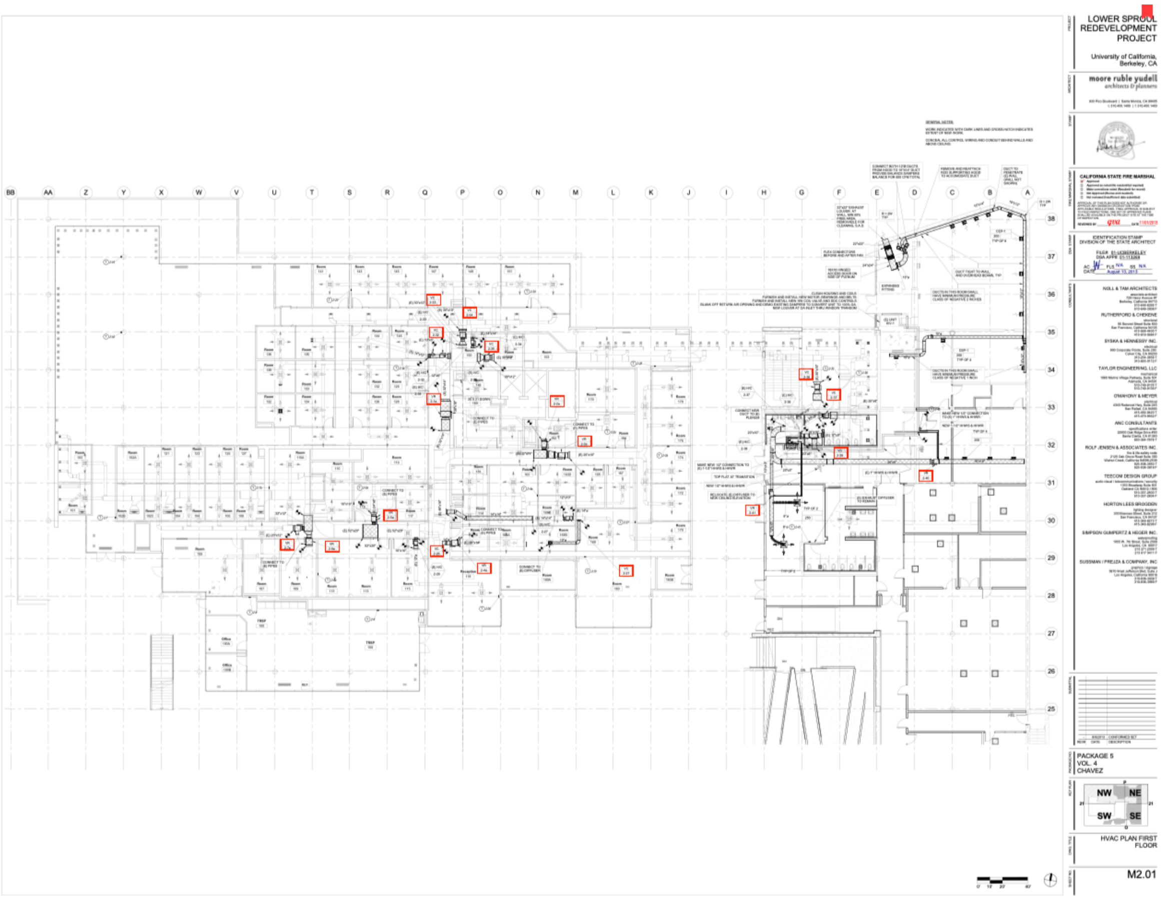

Figure 8: HVAC floor plan from record archives demo

Next, we located the VAV unit and followed its ductwork to determine the serving zones. Sometimes the name of the VAV unit in the archives may not be consistent with the name showed in the ALC system. We suggested sticking to the name in the ALC system because staff from the Facilities Services will keep the system updated. The following figure shows unit VC 2-7a and the serving zones.

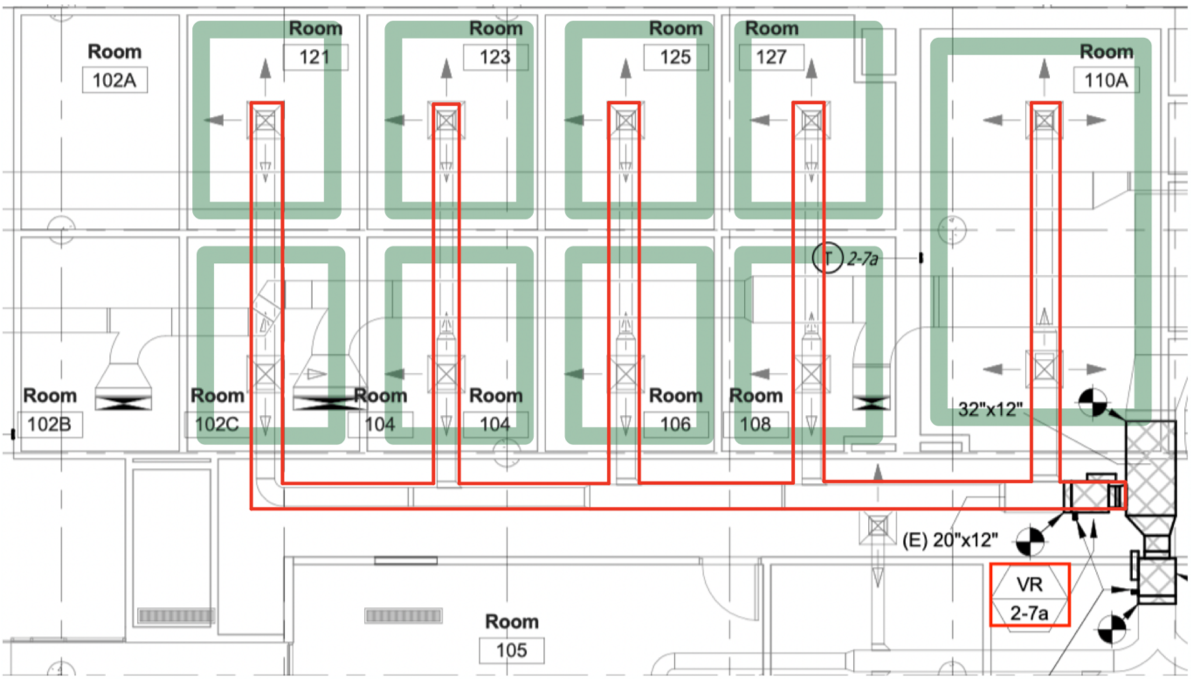

Figure 9: Unit VC 2-7a ductwork and serving zones

From Figure 9, ductwork is highlighted in red, and spaces are highlighted in green. We observed that unit VC 2-7a serves 9 different spaces, including room 121, room 123, room 125, room 127, room 102C, room 104, room 106, room 108, and room 110A.

The last step was to check whether the serving zones shown above aligned with the serving zones in the ALC system for the same VAV unit.

Figure 10: Unit VC 2-7a serving zones in the ALC

4.4.2 Calculate Floor Area of the Serving Zones

While we were cross-checking the mechanical drawings and the ALC system, we noticed that some VAV units served unoccupied space, such as corridors. As a result, we decided to split the floor area into occupied space and unoccupied space. Based on Table 6-1 in the ASHRAE 62.1, we used 0.06 cfm/ft^2 for unoccupied space.

After finding out the unit and its serving zones, we could calculate the floor area of the serving zones using AutoCAD. For this VAV unit, there is no unoccupied space. The serving area equals 1139 ft^2.

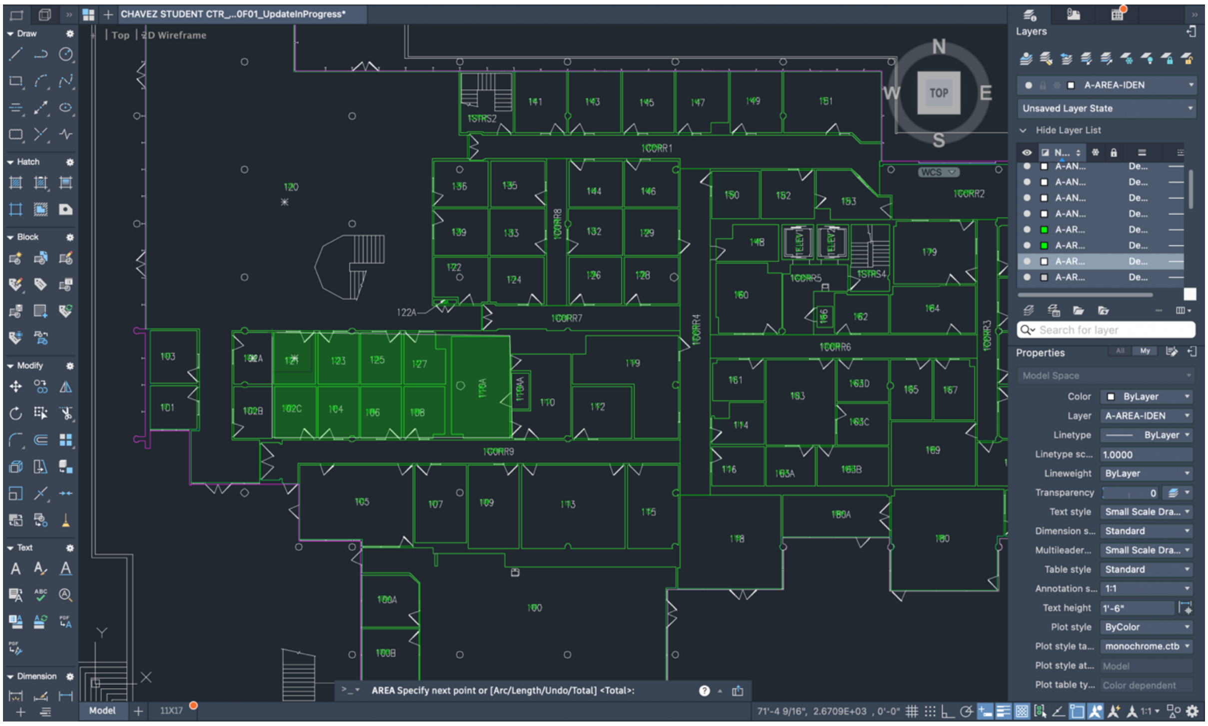

Figure 11: Calculate zone area in AutoCAD

4.4.3 Calculate Occupancy Number for the Serving Zones

The first step was to review the record archives for the building and find the floor plan with the room name as shown below.

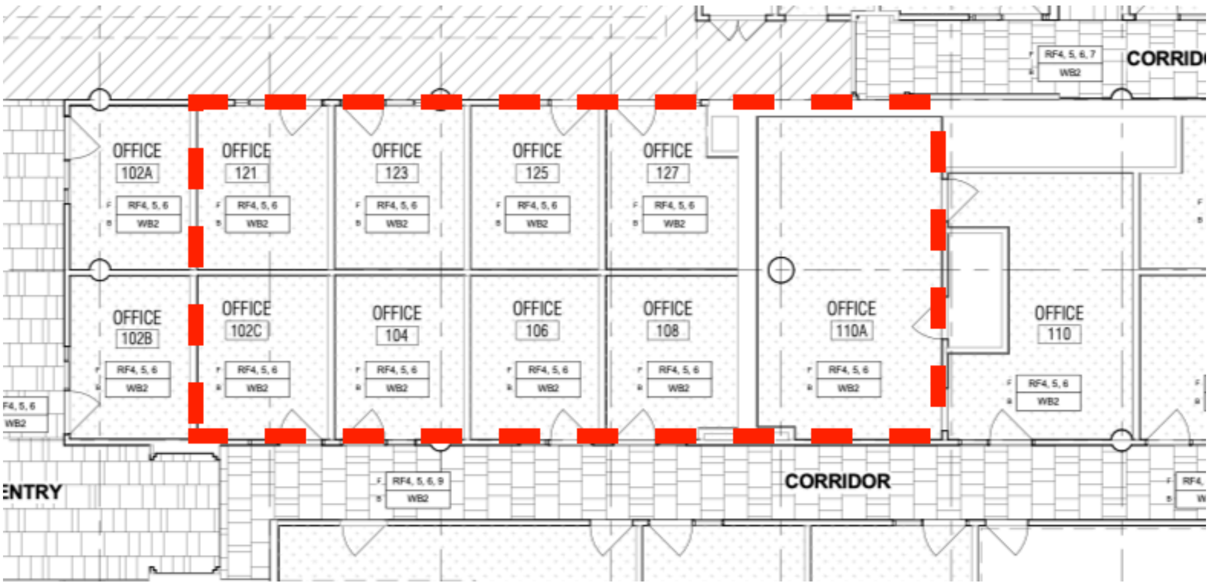

Figure 12: Floor plan with room name

For this VAV unit, all of the rooms are office type. Based on Table 6-1 in the ASHRAE 62.1, the occupancy density equals 5 people/1000 ft^2 for office space. As a result, we assigned 6 people for this space, given that the area equals 1139 ft^2.

The following Table 10 summarized all the occupancy categories used to calculate ventilation zone occupancy for Chavez Student Center from Table 6-1 in the ASHRAE 62.1.

Occupancy Category	**Occupant Density** people/1000 ft^2
Office space	5
Occupiable storage rooms for dry materials	2
Classroom (age 9 plus)	35
Music	35
Reception Area	30
Corridors	0
Break room	25
Kitchen	20
Supermarket	8
Light assembly	7
Art Classroom	20

Table 10: Summary of occupancy categories used for Chavez Student Center

As mentioned before, we suggested conducting an on-site occupancy investigation as well. Because the zone type might change from its original purpose as time went by, and so did the occupancy number, architecture floor plans may not be up to date to catch those changes and cannot accurately reflect the reality of the building condition. As a result, on-site occupancy investigation is necessary, especially for updating the zone minimum airflow setpoints.

In September 2020, we visited the Chavez Student Center and performed the occupancy investigation as shown below. Because the campus was still locked down during that time, most of the rooms in the Chavez Student Center were not accessible. We took other approaches to estimate the valid occupancy number for closed rooms, such as counting the number of monitors and chairs and writing down the number of nameplates mounted on the door.

Figure 13: On-site occupancy investigation

For these 9 office rooms, we counted 10 occupants in total from the field investigation. As a result, we used the larger occupancy number to calculate the minimum airflow setpoints.

4.4.4 Calculate the Minimum Airflow Setpoints

The minimum airflow rate (V_z) to the zone equals the larger of area basis value or occupancy basis as described below:

Area basis: $V_z = 0.15 \cdot occupied\,space + 0.06 \cdot unoccupied\,space$ (1)

Occupancy basis: $V_z = 15 \cdot zone\,population$ (2)

For VAV unit VC 2-7a:

Area basis: $V_z = 0.15 \cdot 1139 + 0.06 \cdot 0 = 171$
Occupancy basis: $V_z = 15 \cdot 10 = 150$

As a result, the design minimum airflow rate for VAV unit VC 2-7a equals 171 cfm.

4.4.5 Find the Current VAV Minimum Airflow Rates in the ALC System

This section will provide a step-by-step guide about finding the ACL system's current VAV minimum airflow rates. The first step was to navigate to the VC 2-7a unit by clicking the Chavez Student Center at the left menu, selecting the 1st Floor drop-down list, and clicking the VC 2-7a unit as shown below.

Figure 14: Navigate to the VAV unit demo

The second step was to find the airflow micro block by clicking the upper Logic tab and scrolling down to the airflow control section, as shown below.

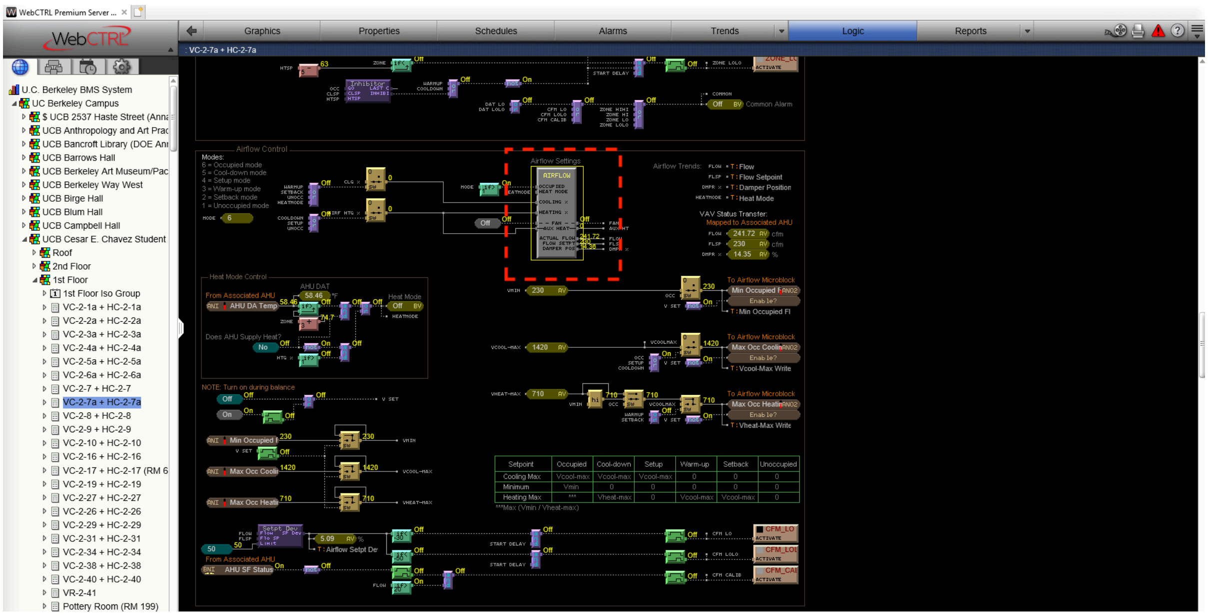

Figure 15: Navigate to airflow micro block

The last step was to click the gray airflow micro block and select the Details tab. The current minimum airflow setpoint for VC 2-7a in the ALC system is shown as 230 cfm in the figure below.

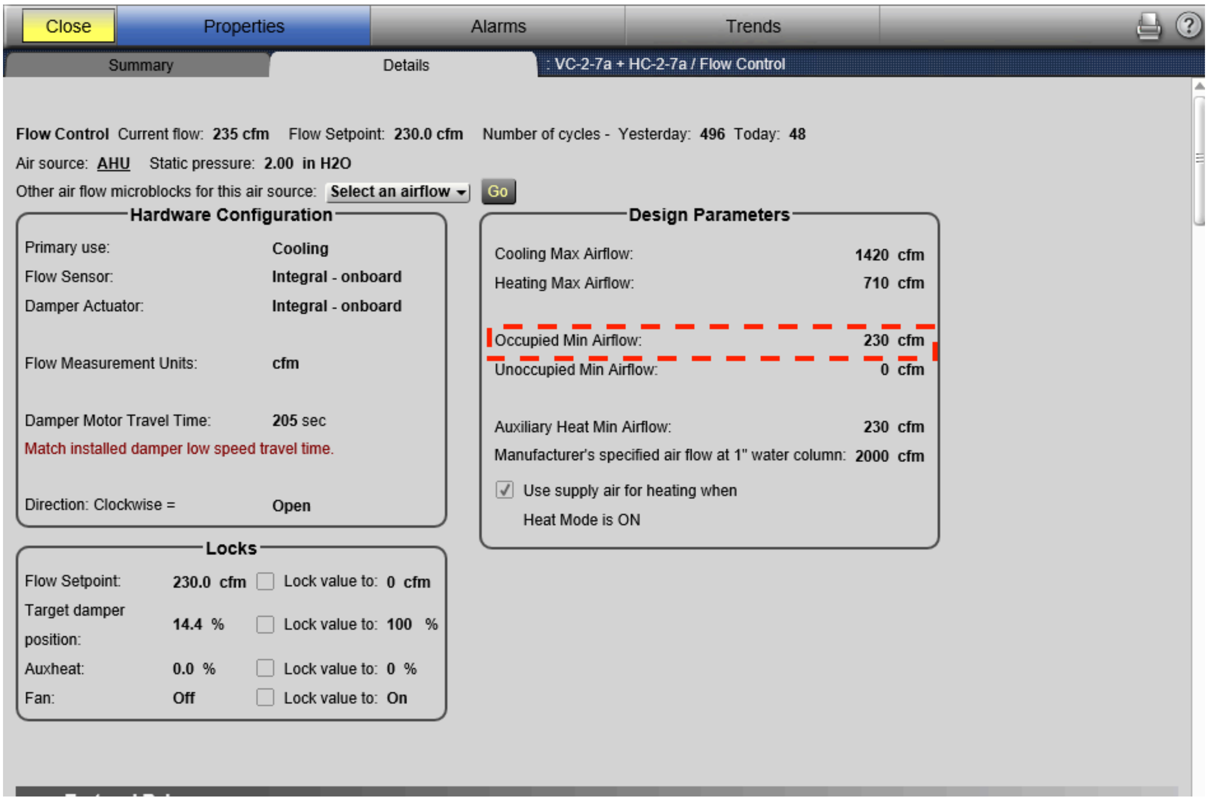

Figure 16: Read the current VAV configuration in the ALC system

In summary, for the VAV unit VC 2-7a, the design minimum airflow setpoint was 171 cfm, and the current minimum airflow setpoint in the ALC system was 230 cfm.

4.5. Estimate Fan Energy Savings for Chavez Student Center

Due to the COVID regulation, we could not make the setpoint changes in the ALC system. Instead of measuring the real fan energy saving, we had to estimate the savings.

We use the following fan curves in the Advanced VAV Design Guide [21] to determine fan energy. The figure below shows the energy impact of the minimum static pressure setpoint on total fan system energy [21]. These fan curves estimate the percent of fan power for a percent airflow at a given static pressure setpoint.

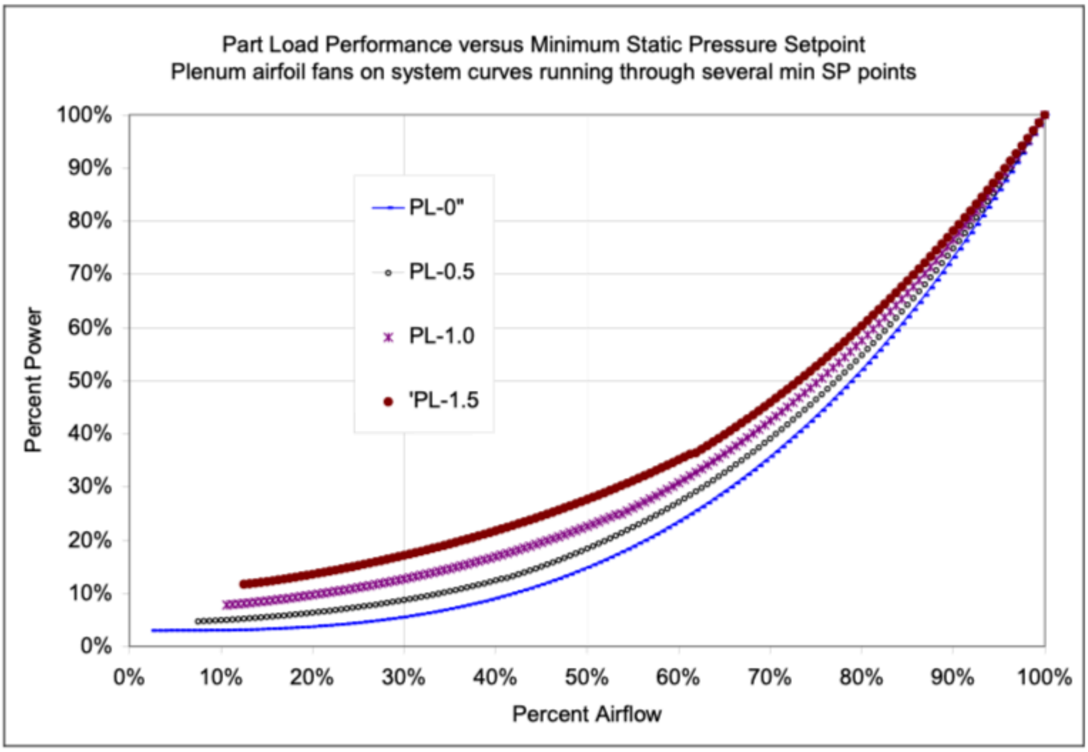

Figure 17: Static pressure setpoint vs fan system energy

We will need to obtain the design power and design airflow for the supply fan in the AHU at Chavez Student Center. From the Lower Sproul Redevelopment Project Bid Package 5-Volume 4 [17], the design power is 40 HP or 30 kW. However, after reviewing the archive for Chavez Student Center in the Box, there is no information regarding the design airflow for the fan. As a result, we need to estimate the value from the ALC system. The design airflow for the supply fan should be at its maximum speed, which is 100%. The design airflow is estimated as 3,5000 cfm based on the trending data below.

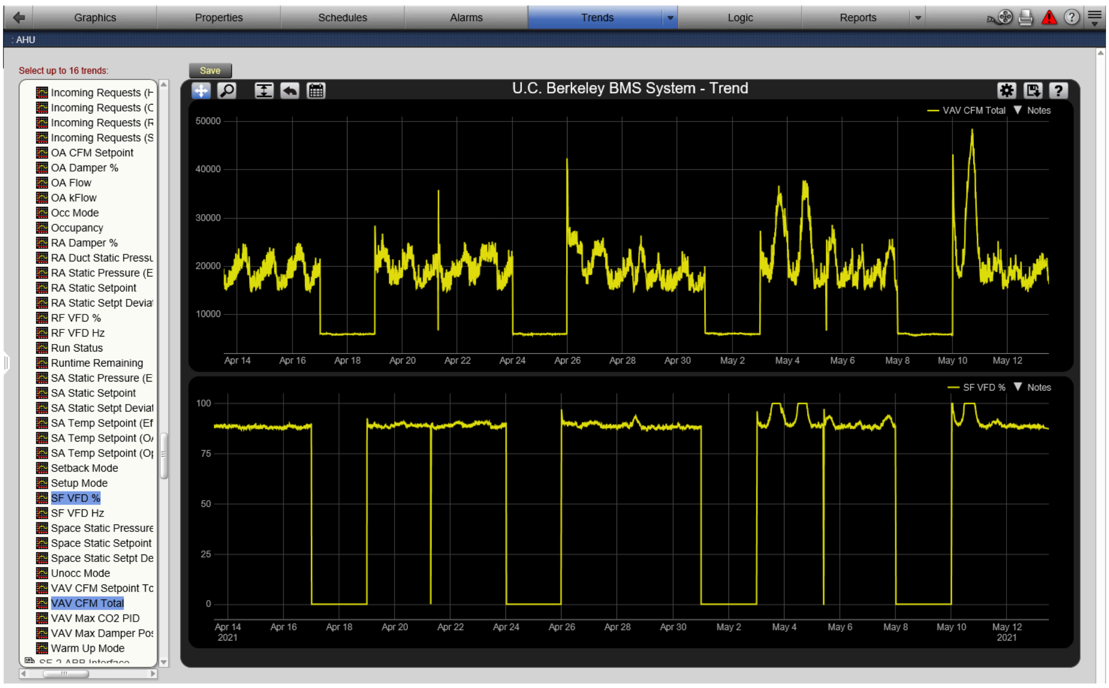

Figure 18: Trending data for supply fan VFD speed and total airflow

5. Results

5.1. Chavez Student Center VAV Minimum Airflow Results

Floor	Unit Number	Zone Served	Floor Area (ft²)		Occupant			Ventilation Min Airflow					Design Ventilation-Min Airflow (cfm)	Current VAV (cfm)
								Area Basis			Occupancy Basis			
			Occupied Space (ft²)	Unoccupied Space (ft²)	Zone Use from ASHRAE 62.1	Occupant Density from ASHRAE 62.1-2016	Peak Number of Ocuupants from on-site Investigation	Min cfm per Area	Min cfm per unoccupied Area	Min cfm by Area (cfm)	Min cfm per Occupant	Min cfm by Occupant		
Basement	VC 2-3	Sub Basement Room A,B,C,D,E,F	790	322	Office	8	NaN	0.15	0.06	137.82	15	120	138	360
	VC 2-4	Room 44, 34, 36, 254, 255	1894	0	Office& Storage	7	NaN	0.15	0.06	284.1	15	105	284	220
	VC 2-6	Band Room 2	2596	0	Light assembly	19	NaN	0.15	0.06	389.4	15	285	389	390
	VC 2-11	Room 15, corridor, half of room 60, room 60A	975	96	Office	5	NaN	0.15	0.06	152.01	15	75	152	820
	VC 2-12	Room 17, 60D, 60C, 66, half room 60, corridor 7, 6, 9	1211	572	Office	7	NaN	0.15	0.06	215.97	15	105	216	1026
	VC 2-13	Corridor 4,5, Room 51,53,57,57A	905	614	Office	5	NaN	0.15	0.06	172.59	15	75	173	400
	VC 2-16	Half the large pavilion 120	2120.5	0	Light assembly	15	NaN	0.15	0.06	318.075	15	225	318	330
	VR 2-18	Room 20B	109	0	Office	1	NaN	0.15	0.06	16.35	15	15	16	200
	VC 2-20	Room141,143,145,147,149	784	0	Office & Classroom	14	40	0.15	0.06	117.6	15	600	600	300
	VC 2-21	Room 41	365	0	Office	2	NaN	0.15	0.06	54.75	15	30	55	360
	VC 2-30	Corridor 1,2,3, Room 72,76,71,73	1642	1417	Office & Music	34	NaN	0.15	0.06	331.32	15	510	510	320
	VC 2-1a	Room 122, 124, 126, 128, 129, 132, 133, 139, 135, 136, 146, 144, 150, 152, 153	1943	1220	Office	10	20	0.15	0.06	364.65	15	300	365	380
	VC 2-2a	Room 148, 160, 166, 162, 164, 179	873	448	Office & Classroom	12	12	0.15	0.06	157.83	15	180	180	210
	VC 2-3a	Room 178, 176, 174, 172, 170	733	222	Office	4	5	0.15	0.06	123.27	15	75	123	841
	VC 2-4a	Room 161, 114, 116, 163, 163D, 165, 167, 163C, 163A	1150	0	Office	6	11	0.15	0.06	172.5	15	165	173	200

First Floor	VC 2-5a	Room 110, 112, 119	726	235	Office	4	NaN	0.15	0.06	123	15	60	123	190
	VC 2-6a	Room 105, 107 109, 113, 115	1479	522	Office & Classroom	28	12	0.15	0.06	253.17	15	420	420	240
	VC 2-7	Room 102A, 102B	196	330	Office	1	2	0.15	0.06	49.2	15	30	49	200
	VC 2-7a	Room 121, 123, 125, 127, 102C, 104, 106, 108, 110A	1139	0	Office	6	10	0.15	0.06	170.85	15	150	171	230
	VC 2-8	Office 100A, 100B	290	102	Office	2	NaN	0.15	0.06	49.62	15	30	50	100
	VC 2-9	TRSP 100	1438	0	Office	8	NaN	0.15	0.06	215.7	15	120	216	170
	VC 2-10	Room 180A, 180	763	0	Office	4	NaN	0.15	0.06	114.45	15	60	114	1400
	VC 2-17	Room 20	2656	0	Light assembly	19	NaN	0.15	0.06	398.4	15	285	398	390
	VC 2-19	Half the pavilion 120	2117.5	0	Light assembly	15	NaN	0.15	0.06	317.625	15	225	318	290
	VC 2-26	Reception 118	471	0	Reception Area	15	3	0.15	0.06	70.65	15	225	225	80
	VC 2-27	Room 163B, 169	408	0	Office	3	3	0.15	0.06	61.2	15	45	61	40
	VC 2-29	Corridor 2	0	445	Corridor	0	0	0.15	0.06	26.7	15	0	27	90
	VC 2-31	Room 70 Room 72A	477	0	Office	3	NaN	0.15	0.06	71.55	15	45	72	300
	VC 2-34	Room 151	305	0	Classroom	11	18	0.15	0.06	45.75	15	270	270	110
	VC 2-38	East-Room 124BZ, Men and Wemen Restroom	1605	0	Toilet Room & Office	20	NaN	0.15	0.06	240.75	15	300	300	450
	VC 2-40	East-Half of Room 130A	650	0	Art Classroom	13	NaN	0.15	0.06	97.5	15	195	195	950
	VR 2-41	Student Initiative	535	0	Break Room	14	NaN	0.15	0.06	80.25	15	210	210	230
	VC 2-14	Mezzanine 201 Left Side	589	0	Light assembly	5	NaN	0.15	0.06	88.35	15	75	88	140
	VC 2-15	Mezzanine 201 Right	980	0	Light assembly	7	NaN	0.15	0.06	147	15	105	147	180
	VC 2-32	Room 236, Room 238, & Room 222	632	0	Toilet Room	8	NaN	0.15	0.06	94.8	15	120	120	140
	VC 2-33	Room 241, 243,245, 247, 249A, 249, 249B	1230	0	Office	7	NaN	0.15	0.06	184.5	15	105	185	240
	VC 2-35	Kitchen 268 and Upper Left of 270	1114	0	Kitchen & supermarket	12	NaN	0.15	0.06	167.1	15	180	180	180
	VC 2-36	Middle part of 270	740	0	Supermarket	6	NaN	0.15	0.06	111	15	90	111	120
	VC 2-37	Office 270B, Storage 270, Men Women RR.	2220	0	Office, Storage & supermarket	14	NaN	0.15	0.06	333	15	210	333	250

	VR 3-1	Room 260 (L,M,N,P,Q,R,& S)	673	0	Office	4	NaN	0.15	0.06	100.95	15	60	101	110
	VR 3-2	Room 260 K & J	255	0	Office	2	3	0.15	0.06	38.25	15	45	45	50
	VR 3-3	Room 242	580	0	Classroom	21	15	0.15	0.06	87	15	315	315	240
	VR 3-4	Room 204, 203, Storage 212A, 212B	458	0	Corridor, Offic & Storage	3	5	0.15	0.06	68.7	15	75	75	80
	VR 3-5	Room 260A	184	0	Office	1	2	0.15	0.06	27.6	15	30	30	30
Second Floor	VR 3-6	Room 260B	184	0	Office	1	2	0.15	0.06	27.6	15	30	30	30
	VR 3-7	Room 260C	184	0	Office	1	2	0.15	0.06	27.6	15	30	30	30
	VR 3-8	Room 260D	184	0	Office	1	2	0.15	0.06	27.6	15	30	30	30
	VR 3-9	Room 260E	184	0	Office	1	2	0.15	0.06	27.6	15	30	30	30
	VR 3-10	Room 213	184	0	Office	1	2	0.15	0.06	27.6	15	30	30	30
	VR 3-11	Room 211	184	0	Office	1	4	0.15	0.06	27.6	15	60	60	30
	VR 3-12	Room 209	184	0	Office	1	1	0.15	0.06	27.6	15	15	28	30
	VR 3-13	Room 207	184	0	Office	1	2	0.15	0.06	27.6	15	30	30	30
	VR 3-14	Room 201C	184	0	Classroom	7	3	0.15	0.06	27.6	15	105	105	30
	VR 3-15	Room 201B	184	0	Classroom	7	NaN	0.15	0.06	27.6	15	105	105	30
	VR 3-16	Room 201A	279	0	Classroom	10	NaN	0.15	0.06	41.85	15	150	150	120
	VR 3-17	Room 260 + Corridors	1269	0	Office	7	7	0.15	0.06	190.35	15	105	190	200
	VR 3-18	Room 202	615	0	Light assembly	5	NaN	0.15	0.06	92.25	15	75	92	100
	VR 3-19	Room 203	634	0	Office	23	25	0.15	0.06	95.1	15	375	375	240
	VR 3-20	Room 240, Room 240A	317	0	Office & Storage	2	NaN	0.15	0.06	47.55	15	30	48	50
Sum													**9,972**	**14,587**

Table 11: Chavez Student Center VAV min airflow rate calculation

From Table 11, the total minimum airflow rate savings in the Chavez Student Center equals 14,587 minus 9,972, which is 4,615 cfm.

The airflow that decreases is the airflow being recirculated between the supply air and return air. The Chavez Student Center has a return fan in the AHU, so we anticipated energy savings on both the return fan and the supply fan. However, it is important to note that we will only see the entire 4,615 cfm reduction when all 59 VAV boxes are at their minimum flow. In reality, this rarely happens as all of the VAV boxes need to operate in the deadband or low heating modes. Depending on the activity in the zones, the actual airflow reduction will be a fraction of the 4,615 cfm at any given time.

5.2. Chavez Student Center Fan Energy Savings

We observed that the main supply fan was typically operating at 18,000 cfm to 20,000 cfm. As an example for the energy savings that would be possible in this building, we set the typical operating airflow as 19,000 cfm. The maximum reduction in minimum airflow is 4,600 cfm, if all zones are operating in the deadband between heating and cooling.

The current percent airflow:

$$percent\,airflow = \frac{operating\,airflow}{design\,airflow} = \frac{19{,}000}{35{,}000} = 54\% \tag{3}$$

The new percent airflow after taking into account the minimum airflow savings:

$$new\,percent\,airflow = \frac{new\,operating\,airflow}{design\,airflow} = \frac{19{,}000 - 4{,}615}{35{,}000} = 41\% \tag{4}$$

The next step was to read the percent power at static pressure equals 1.5 in.w.c. based on the percent airflow value from (3) and (4), as shown below.

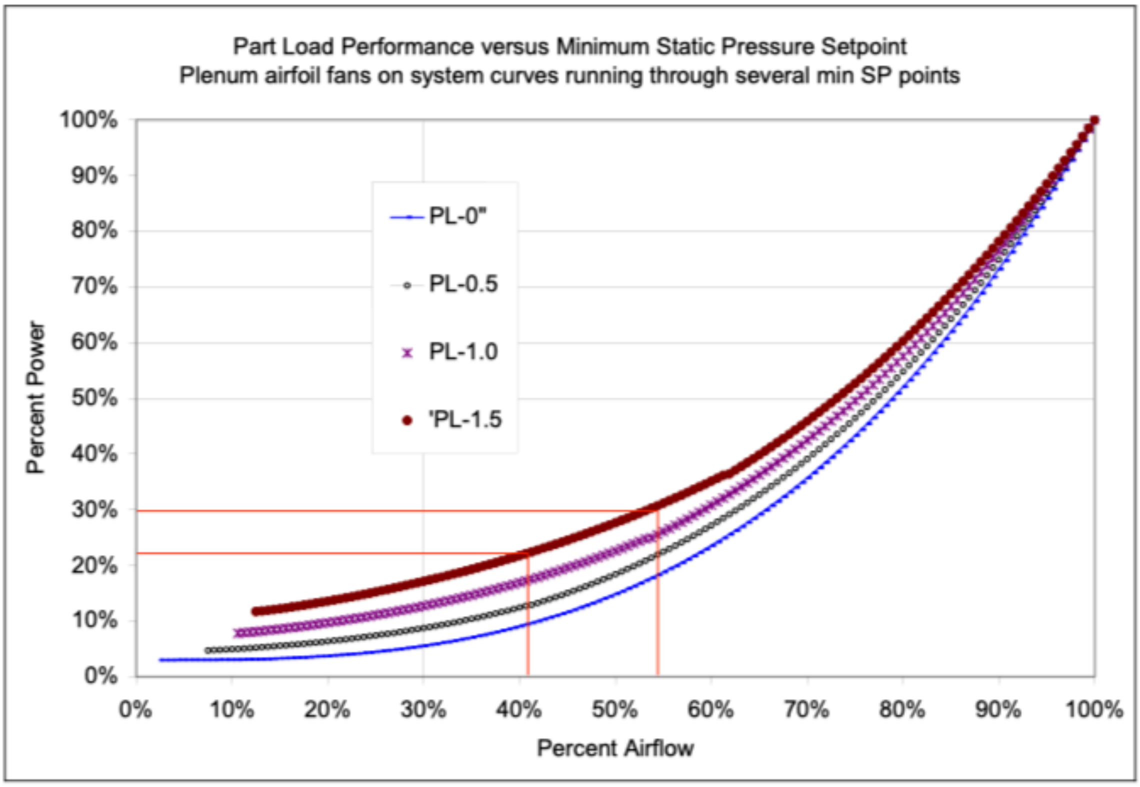

Figure 19: Read percent power based on percent airflow

The current fan power:

$$fan\,power = percent\,power \cdot design\,power = 30\% \cdot 30 = 9\,kW \tag{5}$$

The new percent power after taking into account the minimum airflow savings:

$$new\,fan\ \ power = new\,percent\,power\ \cdot design\,power = 22\%\ \cdot 30 = 6.6\,kW \tag{6}$$

The next step was to compare fan energy consumption before and after the minimum airflow changes.

$$E = W*hr$$

Where:
(7)
E = Fan energy consumption (kWh)
W = Fan power (kW)
hr = operating hours

Table 12 shows the current fan energy, the new fan energy, and the fan energy savings in kWh in one day, one month, and one year.

Hour	$E_{current}$ (kWh)	E_{new} (kWh)	Fan Energy Savings (kWh)
24	216	158	58
720	6,480	4,752	1,728
8,760	78,840	57,816	21,024

Table 12: Chavez Student Center fan energy savings

Even though we did not install meters to measure the magnitude of savings for the heating and cooling side, there will also be heating energy savings and chilled water savings through reducing excessive air recirculation.

6. Discussion and Limitations

This study was conducted in the middle of the pandemic. Inevitably, the COVID had put many restrictions on this project due to the campus shutdown. We started to draft this project proposal to the TGIF committee as early as January 2020 and submitted the grant application in April 2020. At that time, we did not anticipate how badly the pandemic would affect everyone's lives. Moreover, we did not foresee the actions that the campus took in response to COVID-19, especially regarding ventilation strategies in buildings on campus, which will discuss later in this section.

In our original proposal, we planned to review the existing campus buildings and selected the best candidate to demonstrate this energy savings measure at the beginning of the summer in 2020. Then, we intended to install the BTU or steam meter and correct the VAV box minimum airflow setpoints during the summer. We would make those setpoint changes in the ALC system for the candidate building and enable the system to run in the Fall semester. One benefit of this study to campus was to provide measured data of energy savings with the help from installed meters instead of energy savings from simulation or prediction. However, most of the tasks above were either been seriously delayed or canceled due to the pandemic.

The first limitation was the difficulty of finding buildings with meters appropriate for us to measure savings. Most of the buildings on campus don't have a reliable meter to measure hot water consumption. Some of the buildings have steam or condensate meters. However, those meters are either not functional, or broken, or installed incorrectly, or do not connect to the BMS. Besides the hardware limitation, the pandemic also created an extra burden on the costs of time. When we decided to use Chavez Student Center to demonstrate the energy savings measures, we once conducted the on-site steam meter verification. We found out that the meter was never connected to the EMS when installed, so we do not know if the meter was functioning or if the data is reliable. Staff from the Facilities Services helped us to contact an instrument service company to perform the meter investigation. However, due to the personnel changes in the Facilities Services and the communication delays, it took almost four months to have the technician review the meters. As a result, we did not have time to purchase and install new meters to measure data for energy savings.

Additionally, the campus's strategies to accommodate the pandemic impact also added more limitations to this project. As mentioned earlier, on-site occupancy investigation is necessary because the zone type and the occupancy number might change from their original purpose as time went by. However, when we conducted the field investigation in September 2020, most of the rooms in the Chavez Student Center were closed due to the campus closure. Even though we made our best occupancy estimation for some rooms by counting the number of monitors or chairs through windows on the walls, there were other rooms that we could not get any occupancy information as the hallway was closed.

Moreover, following the California Department of Public Health's COVID-19 Industry Guidance for Institutions of Higher Education, the campus modified its ventilation strategies to limit the spread of COVID-19 to faculty, staff, and students [22]. Based on the original project proposal, when the minimum airflow rate setpoints are reduced from high to low, the volume of outside air entering the air handler unit is not changed, as it is controlled to be constant at the air handling unit. Only the volume of recirculated air is decreased, resulting in a higher fraction of outdoor air in the primary air stream. Therefore, there is very little change in actual indoor air quality as measured by the fresh air volume delivered to the occupants in the building. The campus has ventilation system units either using 100% outside air where the air handling unit system always provides fresh air from the outside or using 100% or partially recirculated air where fresh outside air is mixed with return air from the building [23]. However, due to safety concerns during the pandemic, the recirculation damper in the air handling unit in Chavez Student Center was fully closed. As a result, this will impact the fan power savings estimation from correcting the minimum airflow rate setpoints. The results of this study will not indicate a normal operation mode in the building.

Lastly, the 150 year old UC Berkeley campus does not have many buildings with VAV systems. Most of the building automation systems are using Barrington, which has ended service 20 years ago. Only 31 buildings have control systems upgraded to ALC.

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Acknowledgements

This work was made possible through generous funding from The Green Initiative Fund.

I would like to express my deepest appreciation to Dr. Paul Raftery. It was my pleasure working with Paul. Thank you for walking me through the grant application procedures and guiding me immeasurably throughout my research.

I would also like to extend my deepest gratitude to Dr. Stefano Schiavon. It was a great honor for me to have Stefano as my advisor. Even though we could not meet in person in my first year at Berkeley due to COVID, Stefano always served as a great mentor throughout my time at Berkeley.

I would also like to show my deepest gratefulness to Catherine Patton, the former energy analysis at the Energy Office. Thank you for providing your expertise and guidance on this project.

Thank you to Kume Wolde, Evan Oda, and Raul Abesamis from the Facilities Services for giving me the opportunity to work with your team on this project.

Many thanks to everyone at the Center for the Built Environment at UC Berkeley who has provided an excellent research environment for me to work in, especially in this challenging time, and make me feel at home.

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