

An Experimental Approach to Optimizing Automated Hybrid Ventilation in Complex Buildings

by

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Executive Summary

This document is a compilation of the research I have conducted over the past two years in pursuit of my Masters of Science in Civil and Environmental Engineering at the University of Wisconsin – Madison. It is comprised of two stand-alone papers which will be published in academic journals. The idea for this project stemmed from a discussion during commissioning of the Wisconsin Institutes for Discovery (WID). The public space was installed with operable windows and other mechanical components that could be digitally actuated, but the control developed by the contractor did not function properly and did not meet the owner’s needs. The goal of this project was to study the hybrid ventilation system installed in WID and determine if it would in fact save energy and provide comfort to visitors and occupants. If the system worked, then I would develop an automated control to actuate the components associated with the hybrid ventilation system through the building automation system.

The first paper is a compilation of a majority of the work I did in WID with the hybrid ventilation system. This included developing a methodology to test hybrid ventilation strategies within an occupied space, establishing a database to collect data, data analysis utilizing energy and regression models, and finally, comments on the performance of a potential system incorporated within the building. I developed an experimental methodology to find the best way to operate the installed system and utilized the methodology within the building. Data analysis showed significant building ventilation energy savings when utilizing hybrid ventilation in the public space.

The second paper details the automated control that was developed as a product of the first paper’s research. There is no current literature detailing an automated control for hybrid ventilation in complex buildings and my aim was to publish a control that operators could easily implement for their own use. Literature also suggests that novel systems such as hybrid ventilation need to be considered for commissioning, and I developed a methodology for implementing and commissioning this system within a building. I verified the control through computer simulation and ended my time at UW – Madison validating the enhanced commissioning methodology within WID alongside WID staff and UW Facilities Planning and Management’s Digital Controls Group.

Both of these papers will be published in academic journals. The first paper has been submitted to the Journal of Energy and Buildings and the second will be submitted to the Journal of Automation in Construction prior to my graduation. Currently, the automated control has been implemented in the building automation system and is operational in WID. Early performance of this system shows that there is a need for continuous commissioning as the control needs to be modified to meet the needs and comfort levels of those in the building. The control appropriately actuates hybrid ventilation and returns the building to normal, and has shown substantial energy savings in comparison to traditional mechanical ventilation.

Nate Taylor

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Table of Contents

Chapter 1. Optimizing Hybrid Ventilation in Public Spaces of Complex Buildings through Physical

Testing and Analysis	1
Abstract.....	1
1. Introduction	2
2. Background	4
3. Case Study – The Wisconsin Institutes for Discovery	6
4. Objectives and Methodology.....	7
5. Phase I – Test Initialization	9
6. Phase II – Data Collection.....	10
7. Phase III – Testing.....	13
8. Phase IV – Data Analysis.....	14
8.1. Thermal Comfort and IAQ Graphical Analysis	15
8.2. Energy Savings Analysis.....	15
8.2.1. Energy Analysis	16
8.2.2. Regression Analysis.....	17
9. Discussion of Results	19
9.1. Thermal Comfort.....	19
9.2. Indoor Air Quality (IAQ)	21
9.3. Energy Savings.....	22
10. Conclusions	24
11. References	25

Chapter 2. An Automated Control for Hybrid Ventilation in Complex Buildings	29
Abstract.....	29
1. Introduction	30
2. Objectives.....	32
3. Automated Hybrid Ventilation Control.....	33
3.1. Sub-code A: Humidity.....	34
3.2. Sub-code B: Temperature.....	35
3.3. Sub-code C: Energy Use	38
3.4. Sub-code D: IAQ.....	40
3.5. Output Sub-code.....	41
4. Control Verification through Modeling.....	42
4.1. Case Study – The Wisconsin Institutes for Discovery	42
4.2. Computer Simulation	44
5. Hybrid Ventilation Commissioning Methodology	46
5.1. Phase I	47
5.2. Phase II.....	48
5.3. Phase III and IV.....	49
6. Conclusions	51
7. References	51
Chapter 3. Appendices	53
1. Appendix A – Measurement Devices and Specifications	54

1.1.	Sensor Location.....	54
1.1.1.	Hybrid Ventilation Sensors (.xlsx).....	54
1.1.2.	Sensor Locations (.pdf).....	54
1.2.	Sensor Specifications	54
1.2.1.	AHU Sensors (.pdf).....	54
1.2.2.	Zone Sensors (.pdf).....	54
2.	Appendix B – Hybrid Ventilation Testing Notes	54
2.1.	Testing Modules (printed, .docx)	54
2.2.	Anecdotal Testing Notes taken from 9.20.11-10.10.11 (printed, .txt).....	54
2.3.	Comfort Surveys (printed, .docx).....	754
3.	Appendix C – Air-handling Unit Energy Calculations	79
3.1.	AHU Energy Raw Data (.xlsx).....	79
3.2.	EES Source Code (printed excerpt for Mezzanine AHUs, two .ees files and two .lkt files)...	80
4.	Appendix D – Regression Analysis.....	82
4.1.	Weather Data (.csv).....	82
4.2.	EES Source Code (printed excerpt for Mezzanine AHUs, two .ees files and one .lkt file) ...	84
4.3.	R Analysis (excerpt of R code printed, .csv and .R)	86
5.	Appendix E – Indoor Comfort Standards.....	88
5.1.	Wisconsin Institutes for Discovery Design Goal (printed, .pdf)	89
5.2.	Adaptive set point (established through ASHRAE, calculated using EES) (printed, .ees)	91
5.3.	Wisconsin Institutes for Discovery humidity and temperature set points (printed, .xlsx).....	544

6.	Appendix F – Automated Control	96
6.1.	Automated Control Simulation (printed, .ees)	97
6.2.	Automated Control Anecdotal Notes (printed, .docx, .txt)	102

Optimizing Hybrid Ventilation in Public Spaces of Complex Buildings through Physical Testing and Analysis

Abstract

Complex buildings such as hospitals and laboratories require intensive ventilation and cooling loads in order to meet operational demands. One way to reduce energy use while meeting these demanding requirements in complex buildings is the incorporation of hybrid ventilation in areas that do not require high and continuous loads such as public spaces. This research establishes an experimental approach to test and analyze various hybrid ventilation strategies in an occupied, complex building utilizing hybrid ventilation in public spaces. To optimize the use of hybrid ventilation, this research focuses on tracking three performance criteria: energy savings, occupant comfort and indoor-air quality. The framework establishes a variety of hybrid ventilation strategies to test, and outlines how to analyze results graphically and through linear regression modeling. This experimental approach is illustrated through a case study example of a laboratory building located in Madison - Wisconsin, where the selection of the ideal hybrid ventilation strategy for the public space studied resulted in 56 percent average savings in ventilation and cooling load when HV is in use, and established a potential to use hybrid ventilation for 28 percent of the 111 day cooling season (20 percent savings in mechanical cooling over the summer).

Keywords: Hybrid ventilation, Energy savings, complex buildings, natural ventilation, experimental method

1. Introduction

Buildings consume over 40 percent of the total energy produced in the United States each year, and commercial buildings in particular account for 19 percent of total energy consumption [1]. Heating, ventilation and air conditioning (HVAC) most significantly impact building energy use, accounting for 51 percent of total commercial building energy usage [1]. Due to high HVAC energy demands, this system is often the target for energy savings, especially in complex buildings such as laboratories and hospitals that require exceptionally high loads to operate [2]. A study of complex buildings with high process loads shows that these buildings use up to five times more energy than typical commercial buildings [3]. One way to reduce the high HVAC energy demand in these buildings is to incorporate hybrid ventilation (HV) in public spaces [4].

Hybrid ventilation integrates natural ventilation and mechanical cooling when a building's ventilation needs cannot be met naturally. The incorporation of natural ventilation has been utilized in buildings since the dawn of the built environment and is often harnessed through two natural phenomena: cross-flow and buoyancy driven ventilation. Cross-flow ventilation refers to air-flow caused by a pressure differential from one side of the building to the other through open windows or louvers. Buoyancy, or stack effect ventilation, is bulk movement of air due to temperature stratification in spaces with high ceilings (e.g., atria) out of the top of the building. These two natural ventilation phenomena are illustrated in Figure 1, a cross-sectional view of the case study building, and have the potential to significantly reduce HVAC energy consumption, fan energy, and cooling requirements [4]. As can be seen in the Figure 1, cross-flow ventilation results from allowing outside air into the public space (i.e., first floor) through windows located at the periphery. Stack effect, on the other hand, is possible in buildings with existing atria that allow warm air to rise and vent out through louvers in the ceiling.

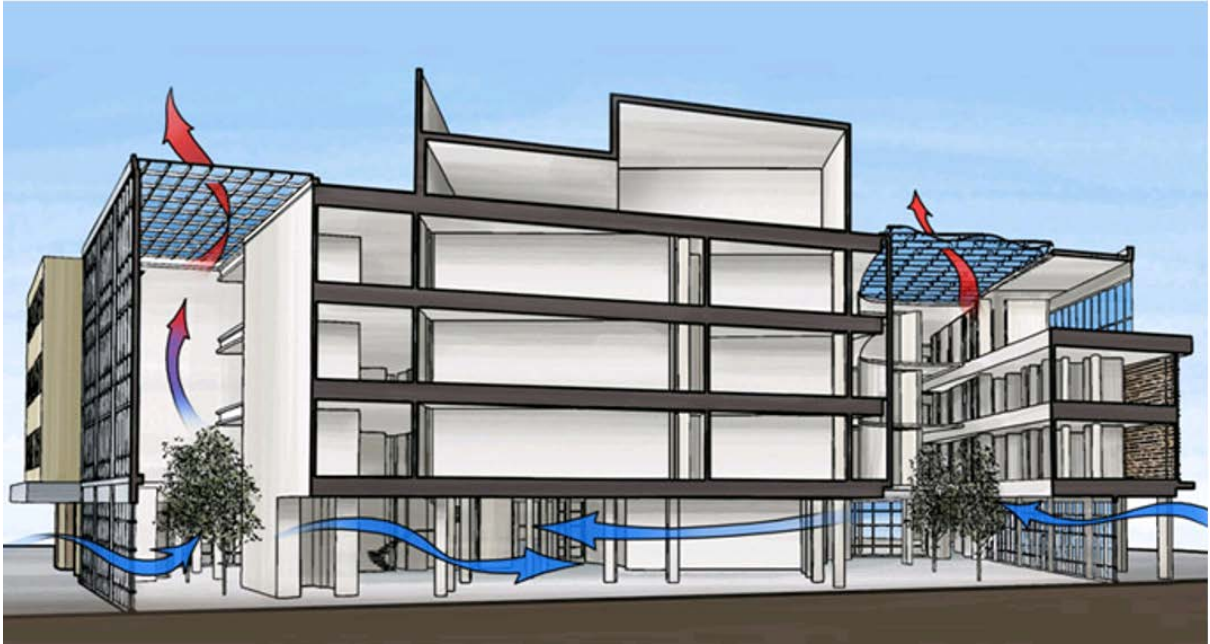


Figure 1 – Sectional view of a building (the Wisconsin Institutes) utilizing cross-flow (horizontal arrows) and stack effect ventilation (vertical arrows)

Most designers considering HV early in the project need to utilize Computational Fluid Dynamic modeling or bulk airflow modeling to optimize building design and control. These packages are often separate from traditional energy modeling software used in industry, and thus require specialists to develop appropriate building models and incorporate them with the building's overall design. Another alternative is to use parametric modeling. This approach is as good as its ability to mimic real conditions in the building environment, and most often requires calibration to ensure that the best HV strategy is being implemented. Due to increased expense of developing a model and the inherent need for real building data, it is often not economical to select an optimal HV strategy through modeling when the system or building has already been constructed and is in operation.

In humid, continental climates that experience hot summers, natural ventilation is difficult to integrate within the building operation procedures without careful planning through design, construction, and building automation, since all ventilation requirements need to be met by outdoor-air (OA) of varying quality and consistency [5]. Additionally, building codes do not facilitate buildings to operate solely through natural ventilation per occupant comfort and indoor-air quality (IAQ) [6], [7]. However, in some

building types like complex buildings where patient rooms or laboratories require continuous ventilation, public spaces may make use of natural ventilation so long as the mechanical systems servicing them are separate from those servicing other areas in the building to allow the airflow to be set back when conditions allow for HV. Complex commercial buildings can overcome obstacles presented through natural ventilation by incorporating mixed mode cooling, or HV, which integrates natural ventilation and mechanical cooling strategies for different locations of the building. It is important to rate the performance of these HV systems, especially in complex buildings that rely on high ventilation rates to mitigate potential contaminants. There are a number of performance metrics that can be tracked to ensure required performance, but three in particular are important to consider when rating a HV system. These include thermal comfort, IAQ and energy savings from traditional mechanical cooling.

2. Background

Several studies document the performance of HV systems in traditional commercial buildings but focus mainly on the first two performance criteria (i.e., thermal comfort and IAQ). The first of these studies established performance metrics to track thermal comfort and IAQ of a Danish HV commercial building model [8]. Likewise, models from a San Francisco building, rated the comfort of occupants in a building utilizing cross-flow ventilation [9]. To bridge the gap between model and reality, Bradley and Utzinger [10] modeled the IAQ of two Wisconsin high performance buildings and calibrated their model with data collected from pollutant testing in the building. Finally, Mouriki et al. [11] collected data from an existing building without a ventilation model to track comfort and IAQ of a Montreal building atrium, and they found significant natural ventilation potential during the warm months of the year. While these studies adequately rated the performance of HV systems with respect to human comfort and health, there is little or no mention of the potential energy savings from implementing this solution.

Intuitively, utilizing HV will reduce mechanical cooling loads; however, there are only a handful of studies that aim at verifying this posit and determining its impact on the overall energy consumption of the building. Zhai et al. [7] modeled the performance of three European buildings utilizing HV, and validated their models with the building's performance. They also outlined necessary data to collect from

buildings for accurate modeling. Two other studies tested HV energy performance through data collected from libraries located in the United Kingdom [12] and Chicago [13]. They found minimal use of mechanical ventilation necessary even in moderate climates through effective control. While these studies track energy performance, they do not make an effort to rate energy savings in comparison to traditional cooling and ventilation.

Current research does not provide adequate measures for testing HV systems that do not involve energy modeling which is the case for many types of new construction and retrofits. Because building ventilation modeling often requires additional monetary and time commitments for design, their development is often considered impractical for systems that are already installed. With no other means of optimizing an installed HV system without a model developed through building design, these systems are often underutilized. More importantly, there is no reference in any of the existing studies to the potential incorporation of HV in complex buildings. Due to the complexity and size of mechanical systems in these complex and high load buildings, utilizing HV in non-critical areas (e.g., public spaces) may prove relatively inexpensive and thus provide a means of low-cost energy savings [14].

This research establishes an experimental approach to collect and analyze data from an occupied complex building to determine which HV strategy is best applied in public spaces to achieve an optimal balance between the three performance criteria (i.e., IAQ, thermal comfort and energy savings). The motivation for this research is the formulation of a method for optimizing an installed or retrofitted HV system, and a general need for case study data to rate HV performance, especially in complex buildings. Instead of creating intricate ventilation models for optimizing HV in existing buildings, this experimental method proposes to test HV strategies and develop criteria for rating performance. Data is then graphically analyzed for thermal comfort and IAQ in comparison to the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) standards [6], [15], [16], while energy savings are determined through linear regression. This experimental approach to optimizing HV is illustrated through a case study example of the Wisconsin Institutes for Discovery on the University of Wisconsin-Madison Campus.

3. Case Study – The Wisconsin Institutes for Discovery

The Wisconsin Institute for Discovery at the University of Wisconsin – Madison’s campus, is a \$213 million research laboratory that was funded by public and private investors and completed in December 2010. This facility is located in a humid-continental climate, and houses biomedical, chemistry and computing researchers in its 4 story 33,000 m² footprint. The basement and top three floors serve as support space and have nine distinguished laboratory zones, which qualify the building as complex. These bio-safety level laboratories require complex mechanical systems to relieve researchers of the possible contaminants they are working with through fume hoods, enhanced filtration of circulating air, and ventilation. The ground floor, or Town Center, is open to the public with conference rooms, study areas, a café, dairy bar, and restaurant covering an area of 4800m². This public space may be opened to the outside environment through operable windows and doors, and is separate from the laboratories.

The Wisconsin Institute for Discovery is an ideal example of a complex building that has the potential to utilize HV in spaces that do not require strict ventilation such as the Town Center shown in Figure 2. The Town Center has two air-handling units (AHU) servicing it separate from the mechanical systems for the laboratories on the top floors. The Town Center AHUs are variable-air-volume systems, cooled with campus provided chilled water, and controlled through a building automation system (BAS). Control actuated windows allow air to flow through the public space (shown in Figure 2 in white is open zone supply) and buoyancy driven ventilation is aided by two large atria (shown in Figure 2 in hashed fill) that are separated from the laboratories on the top floors by a glass façade (shown in Figure 1). Stack effect hot air is exhausted through louvers in the ceiling of the atria and can be mechanically assisted by fans connected to them and located on the roof. Cross-flow ventilation can be utilized through operable windows and wall partitions. While most of the public space can be ventilated through these combined natural ventilation measures, Figure 2 details some areas that do not have direct access to outside ventilation (shown in shaded region is closed zone supply) necessitating AHU ventilation even when HV is implemented throughout the rest of the floor.

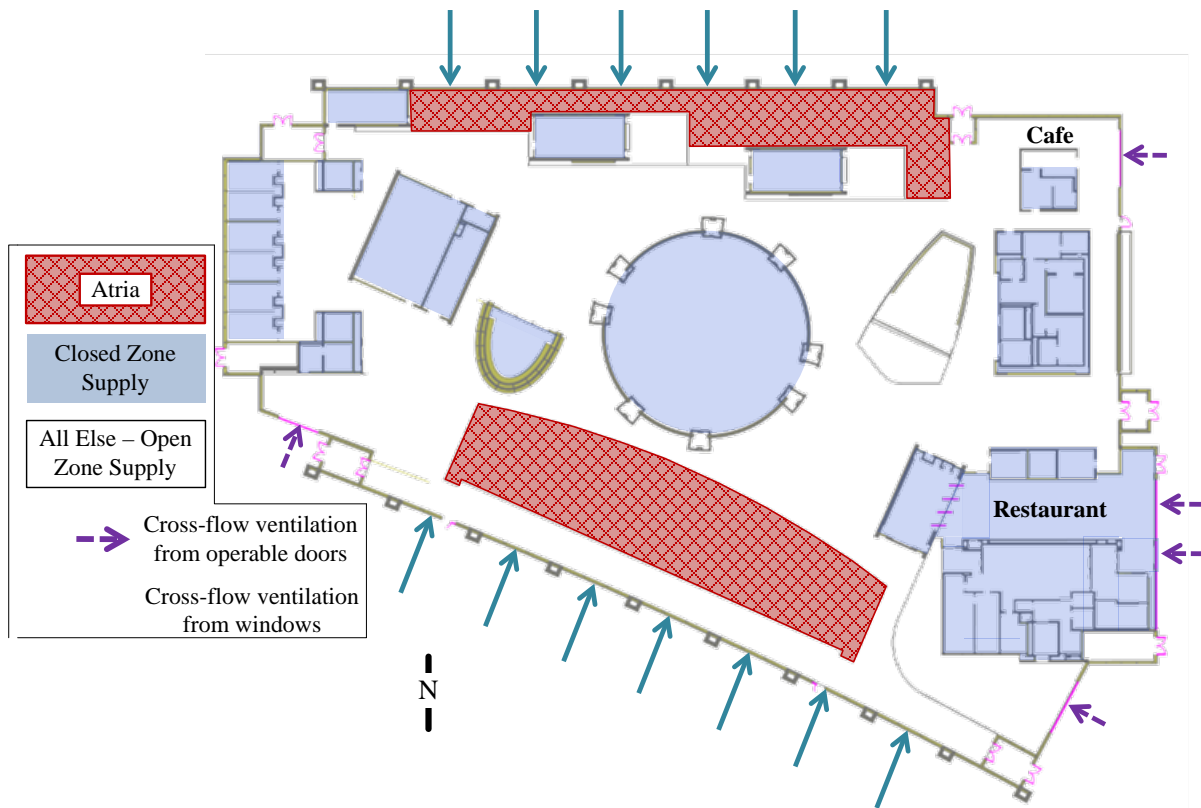


Figure 2 – Town center and 2nd floor HV Diagram

4. Objectives and Methodology

The case-study will be used to illustrate the experimental framework by developing and running HV tests in order to optimize the installed HV system in the public space of complex buildings based on three performance metrics: (1) energy savings, (2) thermal comfort, and (3) IAQ. The objectives are three-fold: (1) develop HV strategies that are appropriate for the space, (2) rate the performance of each strategy in order to select the best one, (3) and determine the expected energy savings from HV in this space, with the potential number of hours this strategy can be applied throughout the cooling season. The objectives are met through the methodology illustrated in Figure 3 by establishing Testing Setup (I), Data Collection (II), Testing (III), and Data Analysis (IV).

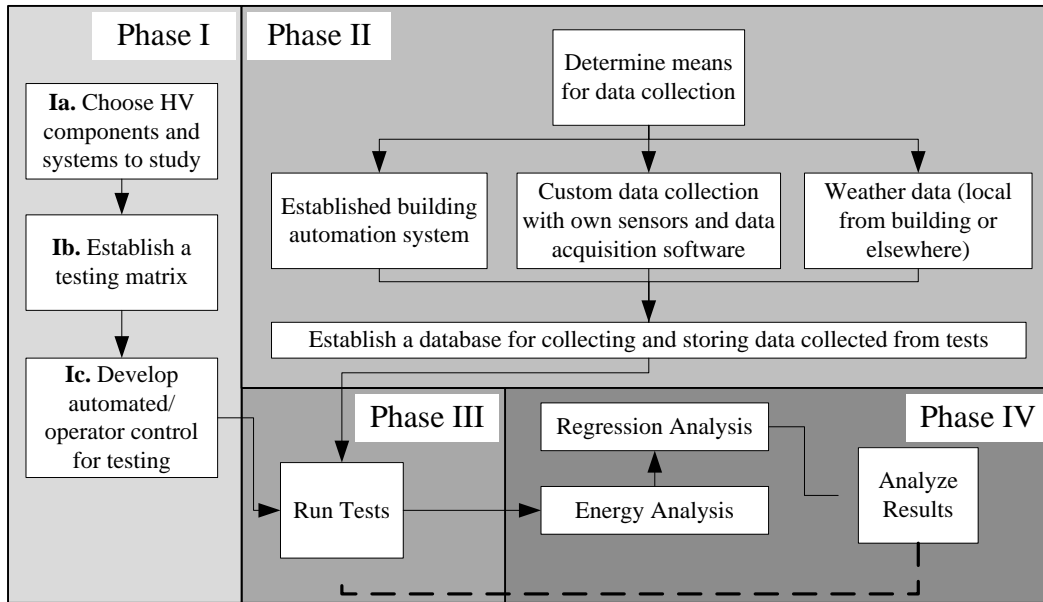


Figure 3 – Experimental Methodology

The focus of Phase I is on the determination of the HV components and strategies to test (Ia), how those strategies will be implemented through a testing matrix (Ib), and how each control will be developed (Ic). To track strategies developed in the experimental matrix, Phase II describes a means for collecting data through building sensors, data acquisition software or other sources (i.e., weather stations and occupancy comfort surveys) and organizing them in a database. Phase III combines the information from the previous two phases and runs tests in order to track the performance of each strategy developed in Phase I. After completing tests, Phase IV discusses the performance criteria for each metric. It also utilizes graphical methods, energy analysis, and linear regression to determine the best HV strategy to implement in the building under study.

Since testing was carried out in an occupied building with nine research laboratories, comfort and IAQ had to be met at all times. Therefore, testing only took place when conditions were adequate to meet ASHRAE standards [6], [16]. Thermal comfort and IAQ were monitored and important conclusions were made based on how these metrics performed during the HV periods. However, based on the developed experimental design, these two metrics were not expected to significantly differ between the strategies tested, but they were monitored as well to make sure they were not affected by using HV. Consequently,

energy savings was the performance metric that was ultimately used to select the best strategy as discussed later in the paper.

5. Phase I – Test Initialization

Phase I establishes what dynamic building components are related to HV; namely, what affects and controls HV in public spaces of complex commercial buildings. The Wisconsin Institutes for Discovery had the ability to use HV in the public space but no strategy had been developed and implemented as part of the building operation protocol. The researchers considered several scenarios and established seven permutations of HV component actuation. The first scenario is traditional mechanical cooling and is considered the Building Base Case Strategy 0.0. The Base Case HV Strategy 1.0 requires the minimum component actuation, and focuses on utilizing cross-flow ventilation through operating the windows. It is considered the Base Case HV Strategy 1.0 because all other HV strategies actuate these two components (i.e., windows **OPEN** and open zone supply **OFF**). Strategy 1.2 is an extension of 1.0 by opening atria louvers to allow warm air to exhaust from the atria thus utilizing stack effect. Strategy 1.4 extends Strategy 1.2 by utilizing the mechanical assisted vent fans to potentially enhance stack-effect ventilation through atria louvers. Strategies 1.1, 1.3, and 1.5 are the same as Strategies 1.0, 1.2, and 1.4 respectively in every aspect except that closed zone supply is **OFF**. They were considered to evaluate the performance of the closed zone spaces without mechanical ventilation from AHUs. The closed zone supply experiments were conducted when those spaces were not occupied. Actual implementation of Strategies 1.1, 1.3, and 1.5 would require automated controls that link the event management system to the BAS or monitor occupancy and then rely solely on HV when these spaces are not being used.

To illustrate these strategies, Table 1 outlines a testing matrix that describes how components and strategies interact. Components, denoted with alpha characters (e.g., A. Windows) are identified at the header of the table. The rows of the table detail the strategy and what components are actuated. The Building Base Case Strategy 0.0 (highlighted in Table 1) references what state each component is in under a traditional mechanical ventilation strategy in gray text. Component actuation is then identified with bold text as OPEN/CLOSED or ON/OFF.

Figure 3 explains the control strategies defined from the rows of Table 1. For simplification, every component is listed for the Base-Case HV Strategy 1.0, and subsequent strategies just include additional component actuation. The control initialization occurs when internal and external conditions are favorable for HV as defined by automated control or the operator. Using the testing matrix and control strategy diagram (linked with alpha characters), HV strategies were tested over a variety of days capturing varying internal and external conditions for each case.

Table 1 – General testing matrix for hybrid ventilation strategies

Test Strategy	A. Windows	B. Open Zone Supply	C. Closed Zone Supply	D. Atria Louvers	E. Mechanical Assist Vent Fans
0.0– Building Base Case	CLOSED	ON	ON	CLOSED	OFF
1.0 – Base Case HV Strategy	OPEN	OFF	ON	CLOSED	OFF
1.1 – HV Strategy 1	OPEN	OFF	OFF	CLOSED	OFF
1.2 – HV Strategy 2	OPEN	OFF	ON	OPEN	OFF
1.3 – HV Strategy 3	OPEN	OFF	OFF	OPEN	OFF
1.4 – HV Strategy 4	OPEN	OFF	ON	OPEN	ON
1.5 – HV Strategy 5	OPEN	OFF	OFF	OPEN	ON

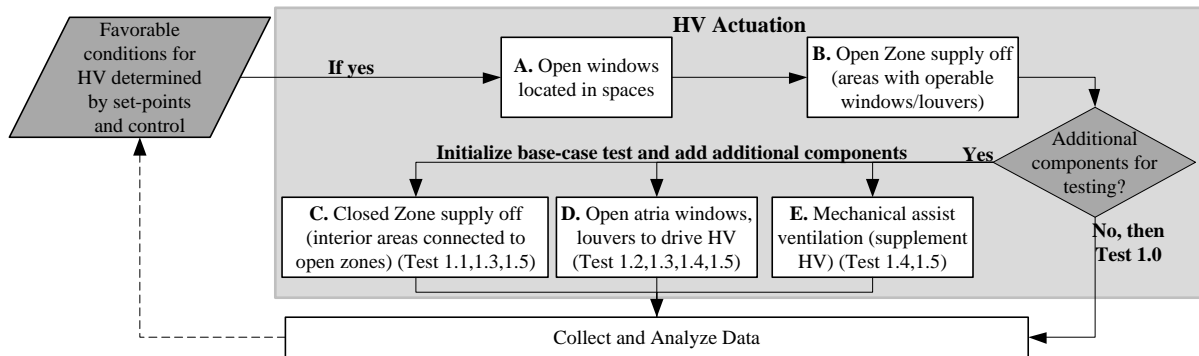


Figure 3 – Varying control strategies based on Test Matrix

6. Phase II – Data Collection

Once the testing strategies were established, a data collection framework was developed to track the three performance criteria (i.e., Energy Use, Occupant Comfort and IAQ) for each strategy established in the testing matrix. Performance metric data was collected from a Niagara based system established in the building to track energy use characteristics. Data was also cross-referenced with Johnson Control’s Metasys Software, which is the building’s HVAC automation system. This data was used to track air-flow from the AHUs and verify temperature and humidity readings taken from the Niagara system. A

commissioning agent was on site throughout the study and verified temperature and humidity sensor readings, as well as pressure and flow rate meter recordings. Supplemental weather data was supplied from a weather station 100 meters from the building and provided all information about the external conditions necessary for analysis.

There are a variety of data that support each metric. For example, thermal comfort is a function of temperature, humidity, airflow, and window position. Additionally, fifty thermal comfort surveys were administered throughout testing to individuals in different locations of the building on different days. IAQ is also a function of temperature, air-flow and window position as well as carbon dioxide (CO_2) concentrations. While CO_2 is not necessarily a contaminant that will harm occupants in most buildings, it is often used as a tracer in industry to monitor how well a system is ventilating a space [13]. As the study assumes that the installed ventilation system provides adequate ventilation, this CO_2 was tracked to ensure that HV provides the same level of ventilation. The primary information of interest to calculate energy savings was OA temperature (T_{amb}), humidity, and ambient static pressure; as well as AHU data: mixed-air temperature (T_{MA} [$^{\circ}\text{C}$]), mixed-air relative humidity [RH_{MA} %], supply-air temperature (T_{SA} [$^{\circ}\text{C}$]), supply-air relative humidity (RH_{MA} [%]), supply-air fan power (P_{SAFan} [kW]), return-air fan power (P_{RAFan} [kW]), and volumetric flow rate (\dot{V}_{SA} [CFM]).

Table 2 was developed to detail the available data from external and internal (i.e., BAS) sources collected to measure the three performance metrics throughout the testing period. In some cases, it may be necessary to instrument the building with additional devices to capture discrete phenomena that the BAS does not, such as internal air-flow measures or zone CO_2 concentrations. This was not done through this study since the thermal comfort and IAQ measurements were not assumed to vary between the testing strategies as discussed in the Data Analysis. Table 2 also details what data to collect and what metric that data supports. It provides a description of what specific location this data was collected from and how the data is related to the study (i.e., why it is relevant to particular metrics).

Table 2 – Data Collection Framework

Data Points to collect	Data Source	Performance Criteria	Placement and Purpose Related to Tests
Window/louver position (inflow air, ceiling or atria)	BAS, Researcher observation	Energy Comfort IAQ	This will denote when windows or louvers are open (I/O).
Occupant comfort surveys	Researcher observation	Comfort IAQ	These surveys will validate the set-points established for thermal comfort as well as provide qualitative information about HV performance from occupants.
Temperature and Humidity	BAS	Comfort	These sensors can be located throughout the public space to capture temperature stratification in spaces with high ceilings and provide comfort information when the building is operating under HV or traditional HVAC (°C).
Airflow Velocity	Researcher instruments	Comfort IAQ	These sensors could be located near louvers, windows or occupied areas. They may help in understanding how air flows through window and door openings and can help substantiate air change rates and comfort but were not tracked in this study since openings were positioned such that there were no draughts (m/s).
Weather	Weather observation unit	Energy Comfort	Of interest to HV are temperature (°C), relative humidity (%), and pressure (kPa).
Mechanical Assist Vent Fans	BAS	Energy	The purpose of these fans is to draw airflow from the windows/louvers, and this additional mechanical energy must be tracked to justify use (kWh).
Air Handling Unit Energy	BAS	Energy	AHUs will be affected by HV and will experience some change in energy use when set-back (for open/closed space set-back) (kWh).
Air Supply to Public Spaces and Atria	BAS	Energy	This data will track air consumption by space. Calculations taking the total AHU load can allocate a particular amount of energy consumption to each zone based on its percentage of the AHU total (m ³ /s).
CO ₂ and other particulates	BAS	IAQ	The standard for tracking IAQ is by measuring zone CO ₂ levels but there are a variety of other contaminants that can be tracked to guaranty adequate fresh air [13] (ppm).

Although studies focused on validating building models suggest that building data should be collected at 1 minute intervals [17], in this study it was determined that averaging fifteen minute data has enough granularity to track the performance criteria. This is because the collected data provided enough resolution to capture environmental changes (e.g., temperature and humidity) and changes in mechanical loads. Since the focus of this study is to determine energy savings over long periods of time, capturing mechanical cycling was not necessary. Finally, this resolution is justified since data collected from the study was used to substantiate energy savings over a long period of time without the need to verify discrete models as stipulated by in Gillespie (2007) [17].

7. Phase III – Testing

The established database was used to track the performance metrics throughout HV testing which took place over the course of two weeks from 9/1/11 – 9/20/11. Of the seven strategies specified in the testing matrix (Table 1), five were carried out in this study. These included Strategies 0.0, 1.0, 1.2, 1.3, and 1.4. Table 1 illustrates that Strategies 1.1, 1.3, and 1.5 are the same as Strategies 1.0, 1.2, and 1.4 respectively in every aspect except that closed zone supply is **OFF**. It was anticipated that turning closed zone supply **OFF** would result in significant energy savings, however Strategy 1.3 was tested and energy savings in comparison to Strategy 1.2 illustrated that this actuation resulted in negligible energy savings. These results showed that Strategies 1.1 and 1.5 would perform similarly to Strategies 1.0 and 1.4 respectively. Therefore, Strategies 1.1 and 1.5 were not tested. As mentioned in Testing Setup, the strategies where closed zone supply was turned off could not be applied in practice anyway, further justifying why Strategies 1.1, 1.3, and 1.5 were not substantially considered.

Since no automated control strategy for HV was in place, the research team in collaboration with building operators determined when HV should be used based on OA temperature, humidity, and comfort levels. Without an existing coordination between the BAS and the building event management system, the only time closed zone supply could be shut off was on weekends when the building was unoccupied. It was hypothesized that Strategy 1.0 would provide the minimum amount of natural ventilation through cross-flow only. On the other hand, Strategy 1.4 would provide the best opportunity for utilizing natural ventilation at the cost of running additional vent fans at the roof of the building to enhance stack effect. In this case, Strategy 1.3 provided a middle ground scenario that combined cross-flow and non-assisted stack flow ventilation. The prevailing indoor and OA temperatures were used to decide which of these strategies to test on a particular day. On cooler days, Strategy 1.0 was run and on warmer days Strategy 1.4 was run in general since it was expected to provide more cooling from outside. Table 3 outlines the strategies that were tested over the two-week testing period along with the number of hours that each test was operated, and the highest OA temperature that day. This table omits dates when no test was run (Strategy 0.0).

Table 3 – HV Testing Strategy Characteristics

Date	Strategy Tested	Duration (hour)	Highest OA Temp. (deg C)
9/28/11	1.2	8	19.2
9/29/11	1.4	6	19.6
10/02/11	1.3	8	18.7
10/03/11	1.3	12	22.1
10/04/11	1.2	9	24.1
10/06/11	1.0	11	25.8
10/07/11	1.0	13	27.0
10/08/11	1.3	18	26.8
10/09/11	1.2	21	24.9
10/10/11	1.4	10	23.4

Due to the fact that these Strategies were implemented on different days where external conditions, internal loads and a myriad of other factors were not controlled, each strategy’s performance could not be directly compared to one another. For this reason a regression model was necessary to determine a baseline energy load for the mechanical systems conditioning the Town Center. The data necessary to statistically substantiate a regression model was taken from the cooling season preceding the test dates from 6/1/11 – 9/20/11 (i.e., 112 days). This time frame provided performance data for the entire summer in which the building operated solely under mechanical cooling. Together, these sets of test data provide adequate information for analysis to determine the expected energy savings from the testing strategies.

8. Phase IV – Data Analysis

The HV data collected in the previous section was analyzed through graphical trending, normalization, and energy analysis. Two trend analyses were completed to rate the first two performance metrics: thermal comfort and IAQ conditions. These trends visually illustrate if and when HV strategies provided adequate measures to ensure occupant comfort and health. The energy savings metric was determined through a combined energy analysis and regression analysis. In this case, the results are both graphical and analytical showing how much energy each strategy saved in comparison to the baseline energy consumption considering traditional mechanical cooling (i.e., test 0.0 in Table 1). This section outlines how each performance metric was rated and includes further discussion about the energy analysis and regression model developed to rate the performance of energy savings.

8.1. Thermal Comfort and IAQ Graphical Analysis

Data pertaining to thermal comfort and IAQ was collected throughout the Town Center at the Wisconsin Institutes for Discovery during the testing period. Thermal comfort was tracked primarily through temperature and humidity sensors. Additionally, carbon dioxide (CO₂) was monitored to track IAQ at the return path for each AHU. The data was compared against ASHRAE Standard 55: “Thermal Environmental Conditions for Human Occupancy” and ASHRAE Standard 62.1: “Ventilation for Acceptable Indoor Air Quality”, both of which provide guidance related to indoor-air (IA) temperature, humidity and contaminant levels [6], [15], [16]. These data are detailed graphically and discussed in detail in the Results Section.

The thermal comfort was monitored throughout testing to avoid using HV on days when conditions were too ‘hot’, ‘cold’ or ‘humid’ based on the operator’s judgment. More specifically, for the test period, the IA temperature had to remain between 19°C (66°F) and 25°C (77°F) and the relative humidity level was maintained between 35-65 percent [6]. The CO₂ concentration tracked through this study provided a measurement of the IAQ metric, and was expected to remain relatively constant whether HV or traditional mechanical ventilation was operating. Each strategy was rated on its ability to keep thermal comfort and IAQ within specifications; however, tests were mostly operated under these conditions by design. As can be seen in the subsequent sections, while these metrics were important to monitor to ensure that they remain within acceptable limits during HV, the results of this research indicated energy savings to be the most important performance metric for strategy selection for this particular case study.

8.2. Energy Savings Analysis

The first step to determine the energy savings from each test strategy was to calculate the energy use profile when none of the HV strategies were employed, and only mechanical cooling was used (i.e., test strategy 0.0). This provided the base case scenario against which the energy use from each of the HV testing strategies was compared. To achieve this objective, data from mechanical cooling of the Town Center at Wisconsin Institutes for Discovery was collected between 6/1/11 – 9/20/11 (a total of 111 days). This data included IA temperature, OA temperature, time-of-day, AHU supply airflow, power

consumption and load. By considering a control volume about the AHUs that service the Town Center, this data was analyzed to calculate energy use of the AHUs (mechanical cooling). These calculations were done using the engineering software, Engineering Equation Solver (EES), a non-linear equation solver with specialized thermodynamic and heat transfer functions [18]. A regression analysis was then performed using the open-source software, R, to develop a base-case energy profile model. This model could be used to compare energy use throughout HV testing to determine energy savings.

8.2.1. Energy Analysis

When HV is used there will still be mechanical cooling energy consumption since some spaces continue to be serviced even with windows and louvers open. Setting back AHUs (instead of turning them off) is also good practice since the fans will never shut down completely thus reducing cycling and cold starts.

Data collected from AHUs is analyzed to obtain energy consumption for the space. Mechanical ventilation energy is determined by considering a control volume about the AHU. The energy inputs to this system include electrical power for fans and a refrigeration cycle or heat exchange with a chilled water system [18]. Fan power can be taken directly from the BAS, but the energy required to cool air and reduce the relative humidity requires the calculation of mixed-air (MA) enthalpy (h_{MA}), supply-air (SA) enthalpy (h_{SA}). This analysis did not consider the energy needed to cool air and reheat for dehumidification. In most cases, this assumption is valid since mixed-air has a humidity ratio below that of the outdoor air. Additionally, HV is used when temperature and humidity are relatively mild necessitating no further dehumidification. While this energy consumption model is valid for periods when HV can be used, it is not appropriate for extreme cold and hot conditions since there will be multiple components involved in air-handling which this model has not taken into account. Thus, AHU energy consumption during TMV or HV is determined by Eq.1:

$$E_{AHU} = [(P_{SAFan} + P_{RAFan}) + \dot{V}_{SA} \times \rho_{Air} \times |h_{MA} - h_{SA}|] \times \Delta time \quad \text{Eq. (1)}$$

where: h_{MA} [BTU/lb dry air] is the mixed-air enthalpy, h_{SA} [BTU/lb dry air] is the supply-air enthalpy,

P_{SAFan} [kW] is the supply-air fan power, P_{RAFan} [kW] is the return-air fan power, and V_{SA} [CFM] is the volumetric flow rate.

Enthalpy is calculated from humidity and temperature readings taken from the AHU for mixed air (or intake air depending on type of AHU) and supply air. This analysis assumes negligible losses to air terminals (i.e., every air terminal has the same duct loss no matter where it is located with reference to the AHU). Regression analysis then provided the ability to correlate AHU energy use to external conditions including OA temperature and time-of-day.

8.2.2. Regression Analysis

This research is interested in quantifying the energy savings generated from utilizing the various HV strategies described in Table 1 without using a building energy or fluid dynamics model. Because of the uncertainty in a number of parameters that affect energy use (e.g., changes in weather, occupancy, load), it is impossible to change only one variable and capture its impact in the system (i.e., track mechanical cooling energy savings by altering various HV actuations). When sufficient real-time data is available, as in the case of the Town Center at the Wisconsin Institutes for Discovery, it is practical to run a series of tests in order to validate which method provides optimal results. In order to select the optimal HV strategy, regression analysis was done to accurately capture performance variations from strategy to strategy in light of external discrepancy in control parameters. A regression model of AHU energy use (E_{AHU} calculated in Eq.1) for periods when HV was not used provides a benchmark to compare various HV strategies. As discussed earlier, when HV is utilized, the AHUs continue to operate, so the energy used while operating each HV strategy was compared against the regression model to determine savings from utilizing HV. “Measuring and verifying energy not consumed is by its nature difficult”, so this regression model was used as benchmark to give a representation of energy use and savings [19].

The statistical, open-source package R was used to generate a linear regression model of the energy use values (E_{AHU}) versus variables that were not originally used to calculate this energy in Eq.1. These variables were collected throughout the study period (i.e., 6/1/11 – 9/20/11), and included day-of-week, time-of-day (hour), OA temperature (T_{amb}), OA relative humidity, calculated OA enthalpy using EES

functions, and atmospheric pressure. As expected, statistical analysis found a strong correlation between AHU energy use (E_{AHU}), and T_{amb} and hour. When these variables were considered, day-of-week, OA relative humidity, OA enthalpy, and atmospheric pressure did not significantly impact the model. T_{amb} and hour were used to produce the linear regression model shown in Eq. 2. The AHU energy use is denoted by $E_{Regression}$ in this equation to distinguish it from the actual AHU energy use calculated in Eq. 1.

$$E_{Regression} = 189.8 - 34.74T_{amb} + 2.35T_{amb}^2 - 0.04T_{amb}^3 + 4.06hour - 0.03hour^2 - 0.04hour \times T_{amb} \quad \text{Eq. (2)}$$

This model fits the data well with an adjusted R^2 value of 0.71, and residual standard error 43.31 on 2,564 degrees of freedom. The summary statistics for each parameter is provided in Table 4 and Figure 4 illustrates the goodness of fit from an excerpt of the data (8/8/11 – 8/30/11), highlighting traditional mechanical cooling necessary to ventilate the Town Center. The figure shows that while this model is a scientific benchmark, capturing the sinusoidal characteristics of the energy consumption throughout the day, it may not adequately capture extremes. As the extremes are under-represented and the most significant savings are during peak hours, savings calculated from this regression are likely lower than actual results. Since the analysis is interested in tracking energy savings, the estimates from this model are considered to be conservative.

Table 4 – Summary Statistics for each Parameter in the Regression Model

	Estimate	Std. Error	t value	p-value
Intercept	252.459	9.714	25.988	< 2e-16
T_{OA}	-43.718	1.613	-27.108	< 2e-16
T_{OA}^2	2.723	0.086	31.738	< 2e-16
T_{OA}^3	-0.047	0.001	-32.478	< 2e-16
Hour	1.991	0.385	5.176	2.45E-07
Hour ²	-0.111	0.012	-9.644	< 2e-16
$T_{OA} \times \text{Hour}$	0.036	0.015	2.444	0.0146

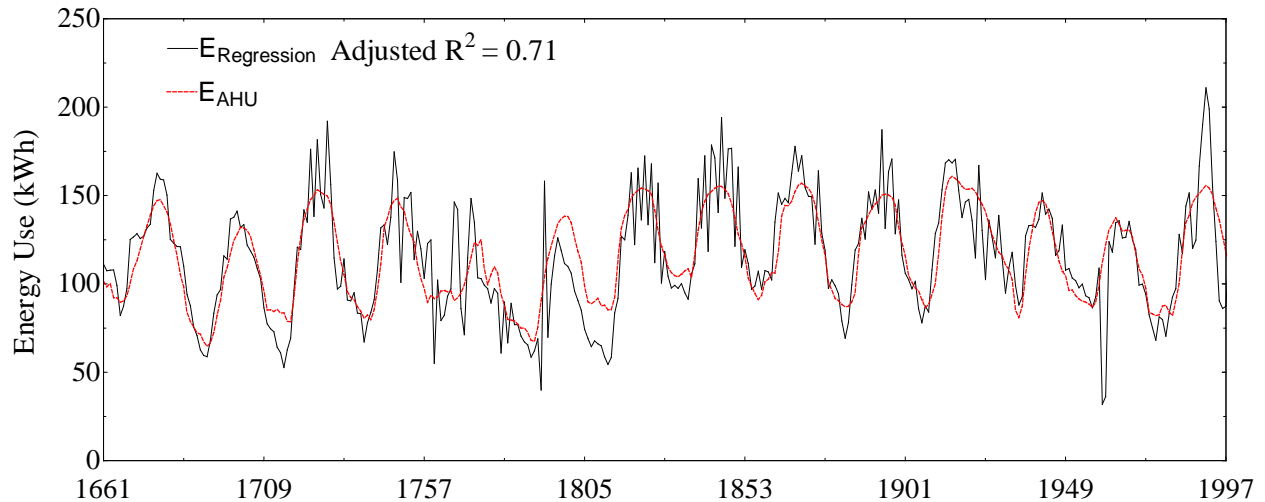


Figure 4 – Comparison of Regression fit to Actual Energy Consumption

9. Discussion of Results

Overall, this study found that implementing HV strategies in the Town Center saved substantial energy in comparison to traditional mechanical cooling while providing a comfortable environment for occupants. Two trends were created tracking IA temperature and IA humidity to monitor thermal comfort, and an additional trend for IAQ was monitored through CO₂ concentration. A final trend and analysis details the energy savings generated through each strategy.

9.1. Thermal Comfort

Results for thermal comfort are shown in Figures 5 and 6 detailing IA temperature and humidity in the Town Center. Figure 5 plots IA temperature over the test period collected for three different locations within the Wisconsin Institutes for Discovery versus the prevalent OA temperature. HV periods are shaded in the figure with the strategy labeled at the top of the shaded region. This plot illustrates thermal comfort of the Town Center (main public space) showing that the temperature remained fairly constant and within the comfort range of 19-25°C (66-77°F) [6], [15]. While the Town Center average temperature always remained within set points, there are a few areas within the Town Center like the café (See Figure 2) that became too warm on days like 10/6 and 10/7. One possible solution for this problem is providing conditioning to spaces that have overheated up to a certain point before returning to traditional mechanical cooling. Another approach studied during this research was to use morning pre-cool by

initializing a HV strategy when OA temperature reaches 14.5°C (58°F) on days with predicted high temperature above 20°C (68°F). This helped maintain a comfortable interior temperature even during the warmer days.

There is a terrace on the fourth floor in the atria which chronically overheated as shown in Figure 5 because stack-effect naturally drew warm air to the upper floors and no shading allowed ample solar radiation to heat the space. This space will most likely determine when stack-effect ventilation can be used in the building to prevent overheating the terrace. This should be taken into consideration if an automated control is to be developed later in the building for HV. While temperature set points are normally viewed as the most important criteria for measuring thermal comfort during HV, humidity is an equally important factor to consider as well.

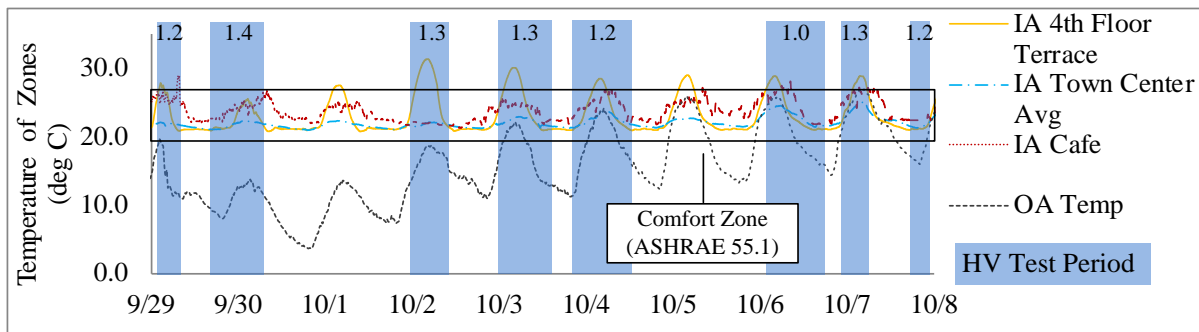


Figure 5 – Indoor Air Temperature in Town Center

Figure 6 illustrates the IA relative humidity and the OA relative humidity through the test period with HV periods shown as shaded. This figure illustrates that when OA humidity increased, so did interior humidity at almost the same rate. This is important when considering the reliability of humidity sensors, which often require continuous calibration to ensure that they are operating correctly. Since IA humidity is strongly related to OA humidity when HV is utilized, there is only a need for one global sensor, which can be calibrated often for accuracy. Throughout testing, the IA humidity remained within the comfort range of 35-65 percent and it is clear that the humidity of Wisconsin’s climate is as much, if not more, of a factor influencing HV operation as OA temperature [6].

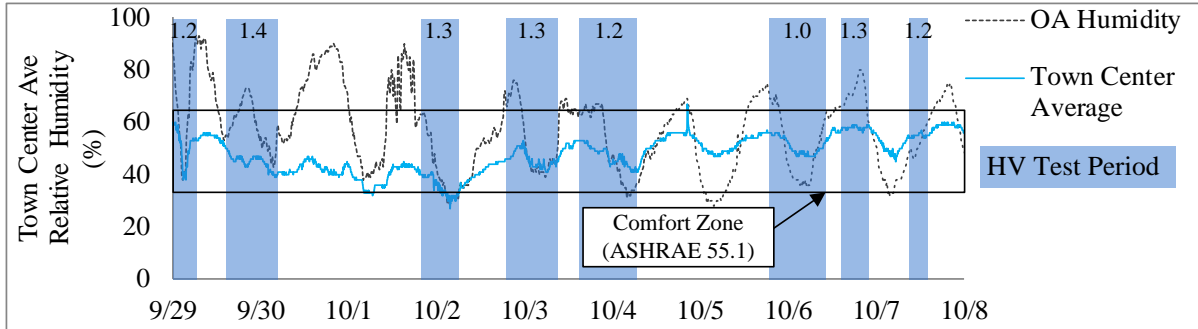


Figure 6 – Indoor Air Relative Humidity in Town Center

Thermal comfort surveys were also completed by 50 individuals who visited and work in the Town Center on the dates of 10/6 and 10/7 where the high OA temperature was 27°C (81°F) and 35 percent relative humidity. These surveys confirm that while most areas in the building were comfortable all day, some areas became too warm especially closer to the building exterior where sun exposure from windows is highest. Results showed that 92 percent of those surveyed were comfortable. The uncomfortable occupants were always sitting in un-shaded areas of the building that were much warmer than the building core or in the café where the heat generation to ventilation ratio was higher than any other space in the building.

Through both surveys and graphical analysis, it was clear that thermal comfort was not a function of the HV test strategy used. This is mainly related to the previous discussion that the HV tests were only implemented when conditions were ‘ideal’. Thus, it is reasonable that no particular strategy outperformed the other based on this metric. This conforms to real practice where HV would only be actuated when internal and external conditions are ideal, so using any of the HV strategies in Table 1 would require these set points be met.

9.2. Indoor Air Quality (IAQ)

IAQ was monitored through CO₂ sensor readings. These sensors were located in each atrium within the AHU return-air intake. Figure 7 shows OA-CO₂ readings in comparison to the two IA-CO₂ readings. Several conclusions can be drawn from Figure 7. First, IA-CO₂ concentration remained around 400 parts-per-million (PPM) in spite of the building’s location between two busy streets in the city of Madison, WI.

In addition, there was no significant difference in IA-CO₂ concentrations between times when HV strategies (shaded areas) were used or traditional mechanical ventilation was used. One reason why IAQ was not affected by the use of HV is because of the large ratio of air volume to contaminants (people and loads) in the large atria. These results emphasize the IAQ was not affected by the use of any specific HV strategy and remained within acceptable ranges for occupancy comfort.

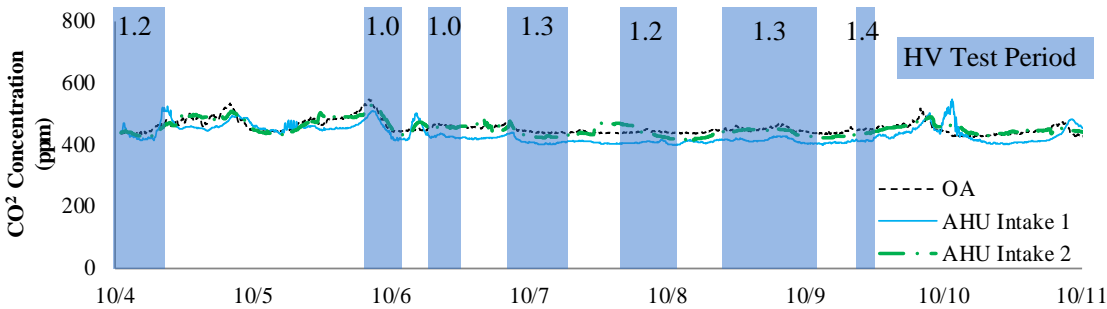


Figure 7 – Indoor Air Quality of Town Center as a function of CO₂ concentration

9.3. Energy Savings

HV testing showed substantial energy savings in comparison to the traditional mechanical cooling regression model using Eq. 2. Town Center mechanical cooling energy consumption through the HV data collection period is shown in Figure 8 in comparison to the regression model. There is an obvious correlation between a reduction in energy use and HV implementation. Figure 8 emphasizes that the Town Center mechanical cooling energy demand during HV strategy testing was substantially less than that predicted using Eq. 2. These savings persist during the warmest parts of the day when energy consumption is usually highest.

The model and HV tests are used to draw conclusions about which strategy saved the most amount of energy on average. Test results are highlighted in Table 4 as an average savings from the baseline determined through Eq. 2 for each day. This table also details the number of hours that each test was run over a variety of days and whether the test was run at night or during the day. As expected, the energy saving potentials are higher during the day when the building is occupied than at night. However, the analysis does not consider the additional savings provided from overnight HV when cold night air is

allowed to pre-cool the Town Center thus reducing mechanical cooling the next day.

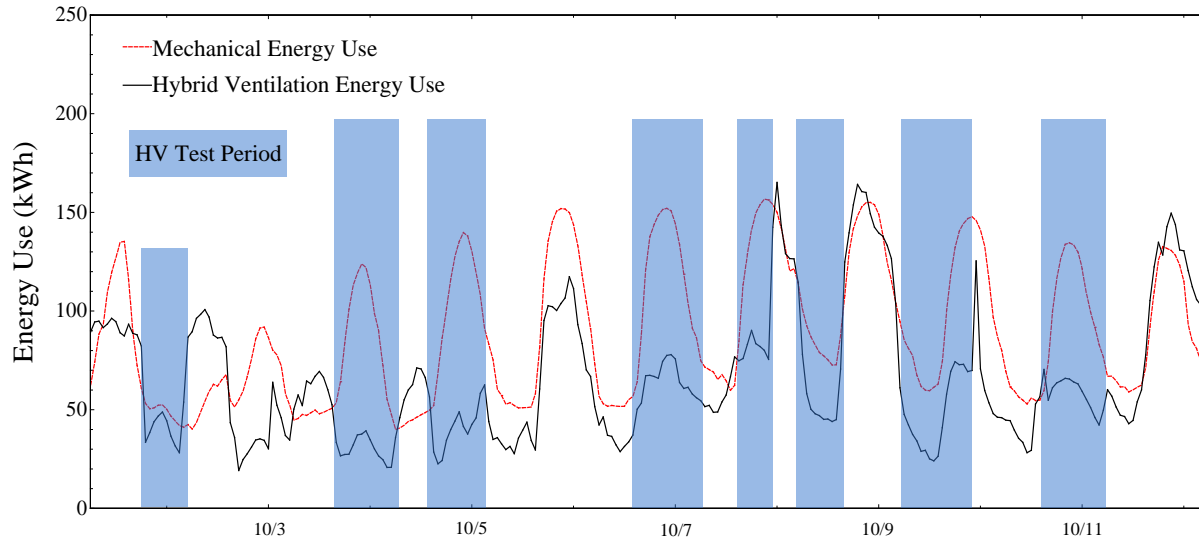


Figure 8 – HV energy savings in comparison to regression model

Table 4 – Hybrid Ventilation Test Results

Test Strategy	Hours Tested	Percent Savings from Baseline
1.0 – HV Strategy 1	21	42.09
1.0 – HV Strategy 1 at Night	6	33.20
1.2 – HV Strategy 2	21	56.58
1.3 – HV Strategy 3	29	56.02
1.3 – HV Strategy 3 at Night	30	34.81
1.4 – HV Strategy 4	10	51.54
1.4 – HV Strategy 4 at Night	6	26.66

The test results show that Strategy 1.2 provides the most savings from the baseline AHU energy at 56.58 percent savings with a standard deviation of 7.88 percent. A sensitivity analysis of the regression model validates these conclusions by showing a 10.20 percent variation between measured AHU energy using conventional mechanical cooling and the regression model for the entire cooling season preceding tests. Thus, these savings are substantial, and far exceed any potential error due to the comparison with regression model.

While strategy 1.3 performs as well as 1.2 in energy performance, it is not a practical strategy to run during occupied periods because it shuts down ventilation to spaces that are not directly located next to windows that might experience high occupancy loads during scheduled events. Code requirements may

not be met if these spaces are under HV when they are suddenly required for unplanned events. This also holds true for Strategies 1.1 and 1.5, which were not tested for same reasons. On the other hand, Strategy 1.4 shows that additional mechanical ventilation used throughout the day results in less energy savings than other strategies while providing negligible benefit on most days. Since the nominal amount of energy saved is not substantial there is added benefit in only running extraneous mechanical equipment when necessary. One such instance would include times when conditions are met for HV yet the atrium terrace has overheated. In such a condition, Strategy 1.4 could be utilized to enhance stack-effect ventilation drawing cooler air up into the atria.

The results from this regression analysis have shown that operators can expect substantial energy reduction when operating HV in public spaces of complex buildings. Considering the previous summer's weather patterns and loads, the system could have operated 372 hours of the 1343 hours (day and night) between June and September or 27 percent of the time. Utilizing Strategy 1.2 when possible would result in a total savings of 6,353 kWh in comparison to the actual mechanical cooling energy consumption of the Town Center without HV which was 32,315 kWh. This equates to a 20 percent total mechanical cooling energy savings for the Town Center over the course of the summer. While the impact of HV energy savings is very important, studies have shown that HV improves occupant experiences in spaces as well, which was also detected from the responses to the survey undertaken as a part of this research [15]. Given these results, there are several other environmental and social factors that should be considered when evaluating the performance of HV. For instance, throughout testing, occupants expressed their favor for having fresh air in public spaces, and restaurant managers agreed that business increased when external façade partitions and windows were open. Additional work should address these factors when utilizing HV in complex buildings and quantifying their impact.

10. Conclusions

Laboratories are complex, energy intensive buildings and the investment in specialized systems to reduce this intensity is being explored in industry. For many of these systems, there is little data that supports protocol for operating and optimizing them. This paper developed an experimental method to

track performance of various HV strategies in public spaces of complex buildings including energy savings, thermal comfort and IAQ. While there are model-based studies discussing the implementation of HV throughout complex building spaces, this research focuses solely on the implementation of HV in public spaces. This retrofit solution is made possible by the fact that the mechanical systems were designed to meet the full load without HV. Future research should consider retrofit solutions for incorporating HV throughout all spaces in complex buildings. Future research related to this case-study will include the implementation of the premier strategy into the building through an automated control. This control will be modeled and then integrated into the BAS where its performance can be monitored and the model validated.

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An Automated Control for Hybrid Ventilation in Complex Buildings

Abstract

Hybrid ventilation is a means of reducing ventilation and cooling loads in buildings while providing occupants with a comfortable environment to work and live. Hybrid ventilation is especially effective in complex commercial buildings which consume a significant amount of energy through their ventilation and cooling systems. This research developed a generic automated hybrid ventilation control for public spaces of complex commercial buildings. The research also identifies a commissioning methodology which monitors the set points established in the automated control and determines the best way to operate an installed hybrid ventilation system in a retrofitted or occupied commercial building. This control was verified through a case study of a complex building in Madison, WI. The results show that the system could be used through 28 percent of the 128-day cooling season resulting in an energy savings of 20 percent in comparison to traditional mechanical ventilation in the public space. The commissioning methodology was validated through implementation of the automated control in the case study building. The results indicate that the hybrid ventilation operation protocol can be determined through commissioning during the operation phase in lieu of developing a complex model of the installed system.

Keywords: Automated control, Hybrid ventilation, Energy savings, Complex buildings, Natural ventilation

1. Introduction

The U.S. Department of Energy's Environmental Information Administration's (EIA) studies show that buildings consume over 40 percent of the total energy produced in the United States (US) each year. Even though commercial buildings are only traditionally occupied throughout a typical work day, they account for 19 percent of total energy consumption in the US [1]. Within commercial buildings, heating, ventilation and air conditioning (HVAC) most significantly impact energy use, accounting for over 30 percent of total energy use, 20 percent of electricity use, and 40 percent of peak demand [2]. Since HVAC systems consume the greatest amount of energy resources in commercial buildings, they are often targeted for energy savings, especially in complex buildings such as laboratories and hospitals that require exceptionally high HVAC loads to operate [3]. These types of buildings have been shown to use up to five times more energy than typical commercial buildings making them excellent candidates for incorporating energy saving strategies [4]. One suggested technique to reducing HVAC energy demand is through the incorporation of hybrid ventilation (HV), a technique mixing traditional mechanical ventilation (e.g., central air-handling units), and natural ventilation [5,6].

Prior to the large-scale incorporation of mechanical ventilation, building spaces were ventilated and cooled by natural ventilation [2]. These types of buildings were ventilated through two natural phenomena, cross-flow and buoyancy driven ventilation, illustrated in Figure 1. Cross-flow ventilation refers to airflow caused by a pressure differential from one side of the building to the other due to the passage of air through windows or louvers. Buoyancy, or stack-effect ventilation, is the bulk movement of air due to temperature stratification in spaces with high ceilings (e.g. atria or stacks). Properly utilizing these natural ventilation phenomena within a building can significantly reduce mechanical ventilation energy consumption [5]. Recent trends focusing on energy efficiency in buildings coupled with the aspiration for more versatility pertaining to occupants' comfort and well-being have led to a re-emergence of building designs incorporating the principles of natural ventilation along with mechanical cooling to create a HV environment [6].

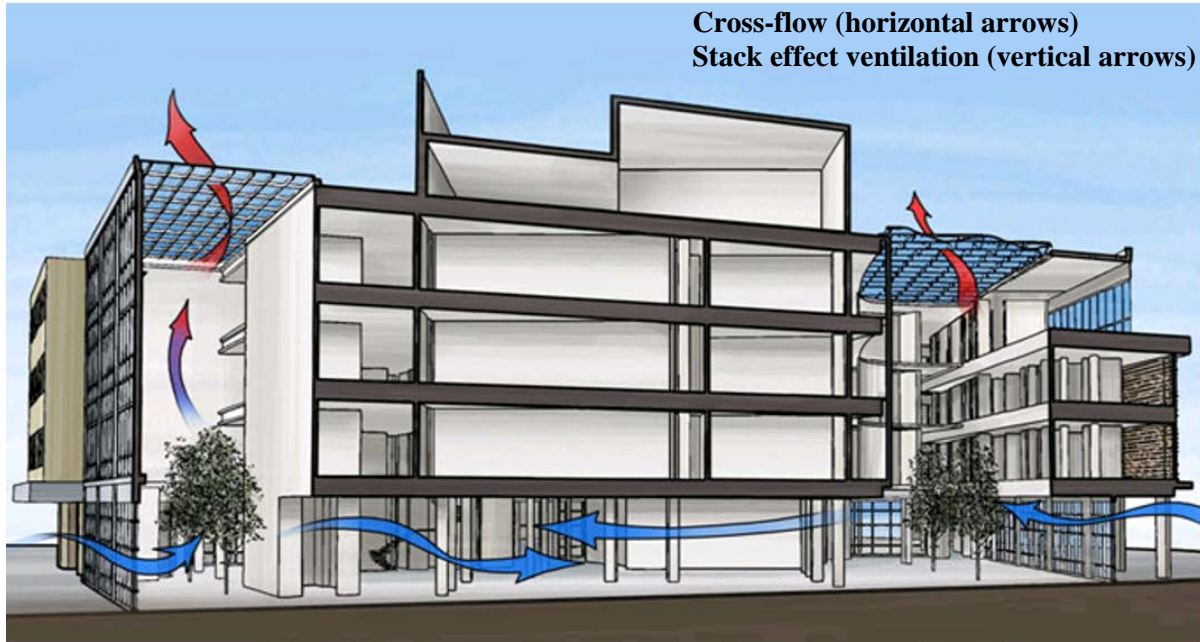


Figure 1 – Natural ventilation in the case study building, Adapted from Ballinger

There are numerous commercial building studies that concentrate on quantifying occupant comfort and energy savings attained through natural and hybrid ventilation in comparison to traditional mechanical ventilation [2,6,9]. In particular, complex buildings represent an important commercial building sector with the potential for implementing HV in peripheral spaces. For example, public and office spaces in hospitals and research laboratories do not require the high ventilation loads that testing laboratories or patient rooms require. Therefore, these spaces can utilize HV as a means of saving energy while providing ventilation that meets indoor-air quality (IAQ) and thermal comfort requirements.

In spite of the many benefits associated with HV, integration of HV in complex buildings has been stifled due to social, economical, and environmental difficulties. This is because most of the ventilation needs are met by outdoor conditions making it difficult to integrate HV in humid, continental climates that experience hot summers without careful planning through design, construction, building automation, and commissioning [7,8]. An additional challenge is that complex computational fluid dynamic modeling or bulk airflow (ventilation) modeling is needed to optimize building design and HV operation during the design phase. This intensive modeling is justified early in a project where its results can help shape the building design and operation; however, the model's worth is diminished substantially once the building

has been constructed and the system installed. It is often not economical to determine an operations protocol through modeling when the system has been installed since ventilation models rely on real data for indoor and outdoor conditions for validation. Instead of developing a model, data collected from a building automation system or other means can be used to determine the best way to operate the installed HV system through a commissioning process.

Commissioning of a building includes a quality assurance process to ensure that building systems perform as intended. As the complexity of buildings increase, the importance of systematically evaluating their performance has increased [7,9,10]. This research developed an automated control for HV that designers, engineers and building managers can use to carry out a commissioning methodology. This commissioning process was designed to determine the best way to operate an installed HV system. The commissioning methodology was validated through application to control the HV system installed at the Wisconsin Institutes for Discovery building located on the University of Wisconsin – Madison campus.

2. Objectives

The goal of this research is to find the best operation protocol for an installed HV system through experimental means rather than relying on ventilation models. This research details the automated control of a HV system utilizing zoned mixed-mode design in a complex commercial building and the subsequent commissioning of that HV system [2].

This research has three objectives:

1. Build upon the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) standards and previous case studies to develop a generic automated hybrid ventilation control for complex commercial buildings [2,6,11–13].
2. Adapt the automated control to a case study of the Wisconsin Institutes for Discovery and verify the control through computer simulation.
3. Develop a commissioning methodology (utilizing the automated control) to determine the best way to operate an installed HV system, which is illustrated through the case study building.

3. Automated Hybrid Ventilation Control

Although manual operation of a HV system may provide more flexibility in control for occupant comfort, it often depends on the judgment of the occupants about indoor and outdoor conditions, preventing facility managers from realizing the full potential benefits related to HV energy savings. To overcome these difficulties, careful implementation of an automated system can provide a very comfortable environment for building inhabitants while best managing HV energy savings since it determines, without human error, the best times to operate the system [14]. The automated system can provide facility managers with a reliable automated control to actuate different HV components (e.g., opening windows to promote cross-flow ventilation, opening atria louvers to promote stack-effect, or setting back air-handling units) to save energy. Since complex buildings often incorporate a building automation system (BAS) for control of traditional mechanical systems, it is prudent to utilize this system to manage an automated control to operate HV when possible [3]. The automated control developed in this research determines whether the space should operate in Traditional Mechanical Ventilation (TMV) Mode or HV Mode based on environmental conditions. Once the space enters HV Mode, a BAS sub-routine actuates a series of HV components used to promote natural ventilation in the space (e.g. opening windows or louvers).

The framework for the automated control, shown in Figure 2, uses the BAS to monitor three performance metrics: thermal comfort, energy consumption of mechanical systems, and IAQ. Thermal comfort is tracked through humidity and temperature measurements, energy savings can be calculated through regression and energy analysis of HVAC equipment, and IAQ may be tracked using carbon dioxide as a tracer gas to determine how well the space is ventilated. This information is input into four main sub-codes A, B, C, and D respectively to determine if established criteria have been met to use HV. If all criteria have been met, each sub-code outputs a true response to the Output Sub-code, which signals the space to operate in HV Mode. When conditions change and HV is no longer feasible (e.g., temperature increases midday), the automated control signals all the ventilation components to switch

back to TMV Mode. Details and schematics of the four sub-codes and output are discussed in the following sections.

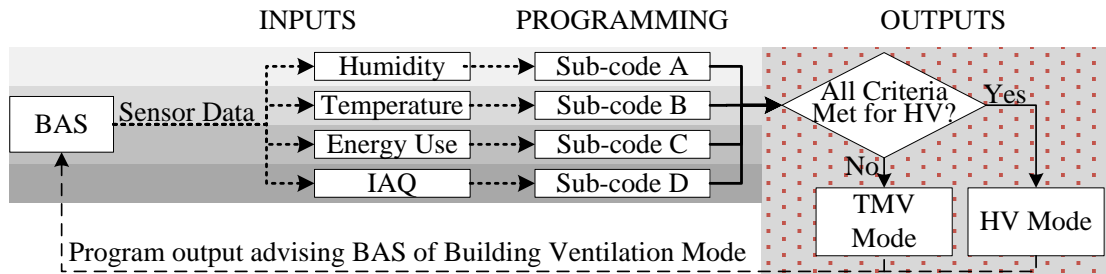


Figure 2 – Automated HV Control Outline

3.1. Sub-code A: Humidity

One primary goal of ventilation is to provide thermal comfort to the building's occupants. Since natural ventilation to the building's periphery is being provided from the outside environment, ambient conditions must be comfortable for occupants. Human thermal comfort is a function of many criteria, but is most often tracked within a space by humidity and temperature measurements.

The humidity sub-code determines whether the relative humidity is comfortable for human occupants. The relative humidity for outside-air (OA) is taken by sensors located outside of the building (normally located on the roof). As shown in Figure 3, the control checks if OA relative humidity (RH_{OA}) is within RH_{min} to RH_{max} (20-70%) as designated by ASHRAE Standard 55: "Thermal Environmental Conditions for Human Occupancy" [12]. If this criterion is met, then the sub-code outputs a true response to the Output Sub-code, noting that each sub-code must be true for the space to operate in HV mode. Taylor and Menassa (2012) have shown that when utilizing HV, the indoor air (IA) relative humidity of a space is very closely related to the RH_{OA} due to dispersion [15]. This is important when considering the reliability of humidity sensors, which often require frequent calibration to ensure that they are operating correctly. Since IA relative humidity is strongly related to RH_{OA} when HV is utilized, there is only a need for one OA sensor (located on the roof) that continuously measures RH_{OA} , and can be calibrated as often as needed for accuracy.

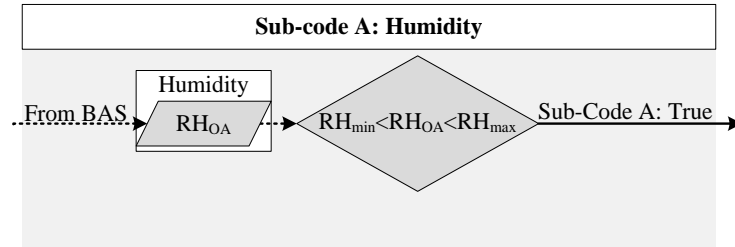


Figure 3 – Sub-code A: Humidity

3.2. Sub-code B: Temperature

Temperature is the second thermal comfort metric that this program verifies because the OA temperature will drive IA temperature when utilizing HV. Sub-code B determines whether internal and external conditions allow for HV based on temperature data provided from the BAS. Outdoor-air temperature (T_{OA}) must be within a comfort range to use HV. These measurements are gathered from sensors located outside of the building (normally on the roof with the RH sensor). Additionally, the IA temperature (T_{IA}) must be maintained within a comfort range for all times. These measurements are collected from sensors located throughout the ventilated public space for HVAC control of air terminals. When considering T_{IA} , values recorded by all the sensors within the ventilated space should be within acceptable limits that meet requirements for occupancy comfort.

This sub-code determines time-dependent temperature criteria as temperature comfort ranges are dependent on occupied and unoccupied hours. The minimum T_{IA} (T_{min}) and maximum T_{IA} (T_{max}) are calculated based on the adaptive model created by Brager et al. and adapted by ASHRAE Standard 55 as shown in Table 1 [12,14]. This adaptive model is a function of the mean T_{OA} (T_{mean}) over the past 30 days with a minimum value of 10°C (50°F) [12].

ASHRAE Standard 55 suggests a minimum T_{IA} ($T_{min,unoc}$) of 12.75°C (54.5°F) for unoccupied hours, and, T_{min} for occupied hours to be determined using Eq. 1 from Table 1. ASHRAE Standard 55 also suggests T_{max} for both occupied and unoccupied periods to be determined by Eq. 2 [12]. In summary, T_{IA} must be within the ranges established in Eq. 3 for unoccupied periods and within the ranges established in Eq. 4 occupied periods.

T_{OA} must be within T_{min} and T_{max} with some variation due to heat generated from within the space by people and equipment. The outdoor-air temperature can therefore be lower than T_{min} and T_{max} by a factor T_{gen} , which reflects the energy generated within the space that will provide additional heating for incoming air during HV. T_{gen} can be obtained through experimentation as the average of the difference between the actual T_{IA} at any given time to the theoretical T_{IA} obtained from Table 1 over a period of time. For reference and through experimentation, Taylor et al. (2012) have found T_{gen} to be 2°C (3.6°F) in the relatively large public space of the case study building (4800m²) [16]. In summary, T_{OA} must be within the ranges established in Eq. 5 for unoccupied periods and within the ranges established in Eq. 6 occupied periods.

Table 1 – Temperature Set Points

Eq #	Value	Set point
Eq. 1	$T_{min}=0.255 \times T_{mean} + 16.4^{\circ}\text{C}$ $T_{min}=0.255 \times T_{mean} + 53.4^{\circ}\text{F}$	T_{min} is the minimum T_{IA} for occupied hours [12]
Eq. 2	$T_{max}=0.255 \times T_{mean} + 21.4^{\circ}\text{C}$ $T_{max}=0.255 \times T_{mean} + 62.4^{\circ}\text{F}$	T_{max} is the maximum T_{IA} for unoccupied and occupied hours [12]
Eq. 3	$T_{min,unoc} \leq T_{IA} \leq T_{max}$	IA unoccupied temperature
Eq. 4	$T_{min} \leq T_{IA} \leq T_{max}$	IA occupied temperature
Eq. 5	$T_{min,unoc} \leq T_{OA} \leq T_{max} - T_{gen}$	OA unoccupied temperature
Eq. 6	$T_{min} - T_{gen} \leq T_{OA} \leq T_{max} - T_{gen}$	OA occupied temperature

The sub-code shown in Figure 4 determines when the space can operate in HV Mode based on temperature. First the sub-code calculates the minimum and maximum T_{IA} from T_{mean} using Eq. 1 and Eq. 2. Then the sub-code determines whether the building is occupied or unoccupied based on input from the building operator (in general commercial buildings are assumed to be unoccupied overnight). If the building is unoccupied then the sub-code verifies that T_{IA} satisfies Eq. 3 and T_{OA} satisfies Eq. 5. When both of these equations provide a true response, Sub-code B outputs a true response.

If the building is occupied, then the program checks if the predicted high T_{OA} is greater than T_{max} . If this is true, then the sub-code verifies that T_{OA} satisfies Eq. 5, otherwise T_{OA} must satisfy Eq. 6. Additionally, T_{IA} is checked by Eq. 4. If an area within the space has overheated due to high heat generation or high solar insolation, then that area is provided mechanical cooling until the area is no longer above T_{max} or until the space returns to TMV Mode. When T_{IA} and T_{OA} criteria are met, Sub-code

B outputs a true response. In this way, the sub-code can either output a true response for unoccupied or occupied periods but not both. This true response is reported to the Output Sub-program.

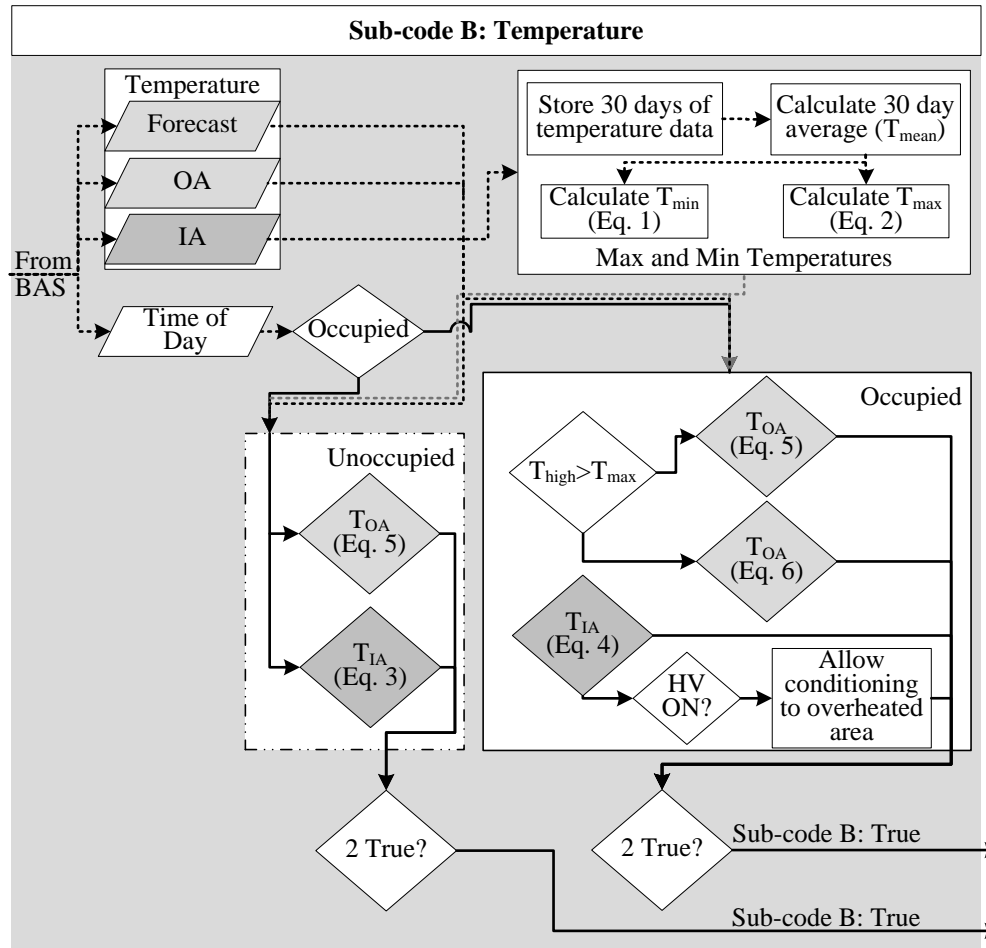


Figure 4 – Sub-code B: Temperature

There are some additional considerations that are taken into account by this sub-code. First, the program can utilize T_{OA} forecasts if they are available through meteorological forecasts input to the program. If the forecasted high T_{OA} for the day exceeds T_{max} , then HV may not be feasible during occupied periods for that particular day. In the case that the forecasted high T_{OA} for the day exceeds T_{max} , HV can be initialized when the building is in occupied mode so long as the T_{IA} and $T_{OA} > T_{min,unoc}$. This feature, more commonly known as night purge, will pre-cool the public space by flushing warm air from the space, thus saving cooling energy later in the day when T_{OA} is expected to be high and TMV is necessary.

Another important consideration is the overheating that may occur during the day for certain areas of the public space. This space overheating can be due to direct sunlight exposure or because internal generation in the area exceeds that estimated through experimentation. If a specific area overheats while the space is in HV mode, the area may be mechanically cooled while the rest of the space utilizes HV. This can only be achieved if the mechanical design allows for air-handling units (AHUs) servicing interior zones to spot cool the overheated areas with little additional energy consumption. In this case, if the specific area's temperature sensor (T_{IA}) records a value exceeding T_{max} , the AHUs will service the area's air-terminal in order to cool the overheated space until the space returns to acceptable set point, or the whole public space returns to TMV Mode.

3.3. Sub-code C: Energy Use

Sub-code C examines energy savings attained from utilizing HV. In order to measure energy savings, a regression model of AHU energy usage during traditional mechanical ventilation needs to be developed. The energy saved when the building is operating in HV Mode is the difference between the expected AHU energy use during TMV and the reduced AHU energy use during HV. It should be noted that the AHUs continue to operate when the building is in HV as some spaces continue to require mechanical ventilation. The primary information of interest to determine AHU energy use during both TMV and HV is shown illustrated in Figure 5 which is a simplified schematic of an AHU using recycled return air from the building. All data outlined in the figure can be obtained from the BAS.

Data collected from AHUs is analyzed to obtain energy consumption for the space. Mechanical ventilation energy is determined by considering a control volume about the AHU. The energy inputs to this system include electrical power for fans and a refrigeration cycle or heat exchange with a chilled water system [17]. Fan power can be taken directly from the BAS, but the energy required to cool air requires the calculation of mixed-air (MA) enthalpy (h_{MA}) and supply-air (SA) enthalpy (h_{SA}). This analysis did not consider the energy needed for dehumidification. In most cases, this assumption is valid since mixed-air has a humidity ratio below that of the OA. Additionally HV is used when temperature and humidity are relatively mild necessitating no further dehumidification. While this energy consumption

model is valid for periods when HV can be used, it is not appropriate for extreme cold and hot conditions since there will be multiple components involved in air-handling which this model has not taken into account. Those caveats considered, AHU energy consumption during TMV or HV is determined by Eq.7:

$$E_{AHU} = [(P_{SAFan} + P_{RAFan}) + V_{SA} \times \rho_{Air} \times |h_{SA} - h_{MA}|] \times \Delta \text{time.} \quad \text{Eq. 7}$$

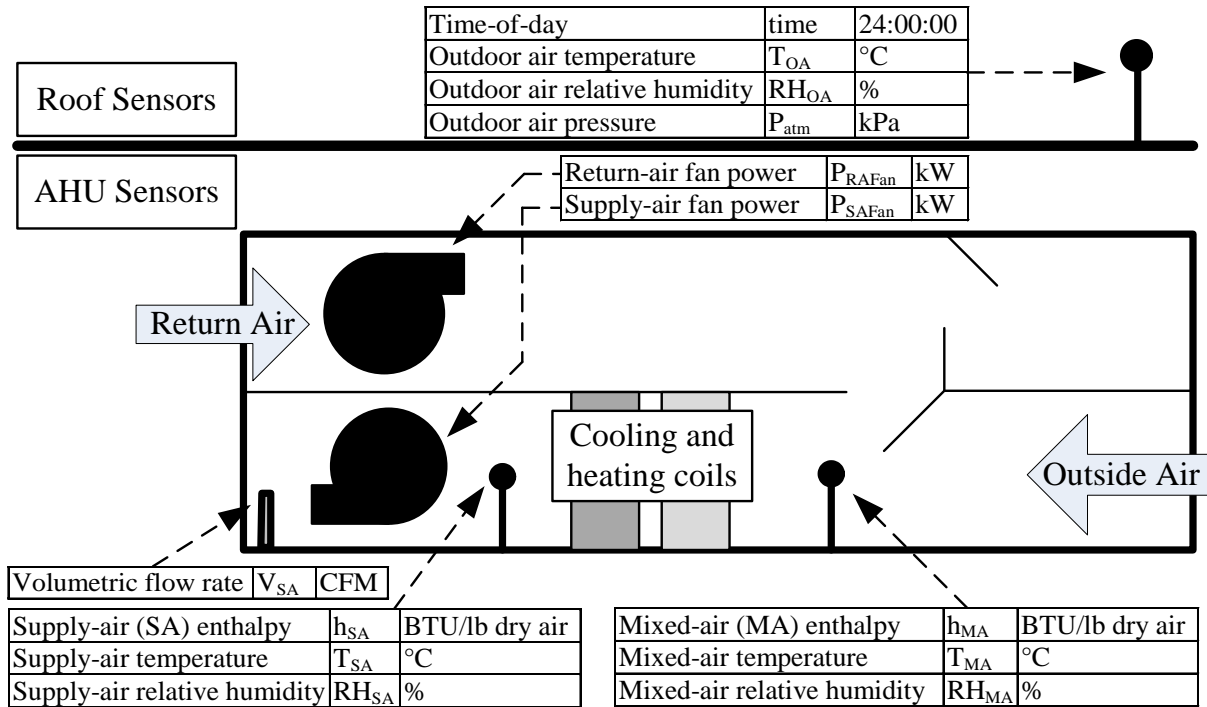


Figure 5 – Data Collected for Energy Analysis

A benchmark of the TMV energy consumption can be created utilizing a linear regression model with the AHU energy consumption as a function of T_{OA} and time-of-day. Taylor et al. (2012) provide a detailed methodology for developing this regression model to compare TMV energy consumption against energy consumed when HV is utilized for a particular space [16]. The regression model developed for the case study building is presented in Section 4.

Figure 6 outlines Sub-code C and details the inputs as AHU data, T_{OA} and time-of-day. The sub-code calculates mixed-air and supply-air enthalpy from temperature and humidity data, and then uses Eq. 7 to calculate AHU energy consumption. T_{OA} and time-of-day are used to calculate energy use from the regression model (E_{RM}) to represent predicted energy usage if the space were to be cooled using TMV. Expected energy savings are then calculated, and averaged over hourly periods to buffer inconsistencies

($E_{Savings,ave}$). These energy savings are then compared to a benchmark energy saving percentage ($E_{Savings,BM}$). As discussed later in the paper, experimentation at the case study building has shown that energy savings in public spaces are expected to be significant ranging from 30-70 percent and averaging 56 percent [16]. To ensure that the system is effective from an energy saving perspective, a minimum value of 30 percent was established as the benchmark energy savings for the case study building as this was the lowest recorded savings documented by Taylor and Menassa [15]. This value limits additional cooling supplied to air-terminals that are turned on to cool spaces that have overheated. In this case, the system will return to TMV Mode when HV is no longer effective. Sub-code C then outputs a true response to the program if the $E_{Savings,ave}$ are greater than $E_{Savings,BM}$.

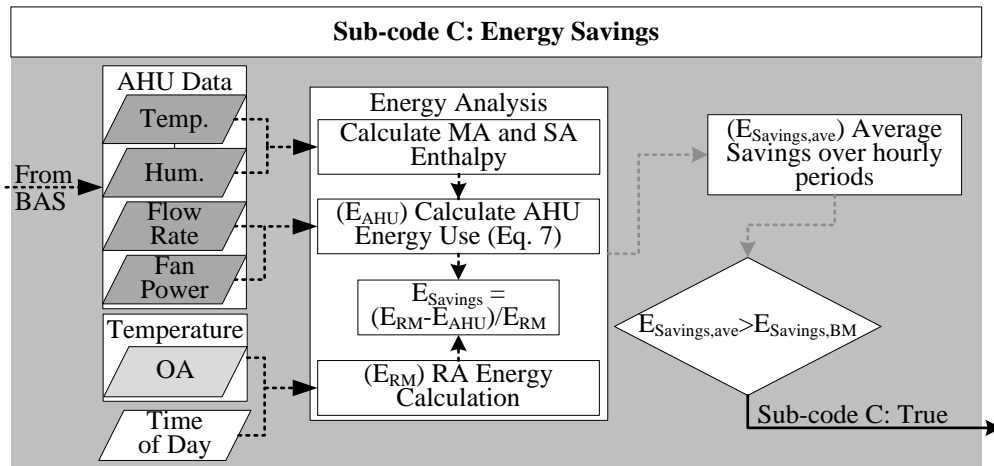


Figure 6 – Sub-code C: Energy Savings

3.4. Sub-code D: IAQ

Indoor-air quality presents big a challenge for HV implementation and must be monitored to ensure that the system provides fresh and safe air quality for occupants. The HV system is designed such that IAQ measures set by ASHRAE Standard 62.1: “Ventilation for Acceptable Indoor Air Quality” are met to make certain that the system promotes a healthy environment. In most cases a HV system will be designed such that it meets the minimum indoor-air changes necessary to ensure adequate IAQ. It is assumed that if minimum indoor-air changes are met then the space will have an acceptable level of contaminants associated with proper building health. To track minimum air changes, it is acceptable to

track CO₂ concentration as a tracer gas for how well a building is ventilated since occupants within the space continuously generate CO₂ [18]. To address IAQ concerns, Sub-code D, shown in Figure 7, appropriately checks that the difference between IA CO₂ concentration and OA CO₂ concentration is no greater than 400 parts-per million [18]. If this criterion is met, then Sub-code D outputs a true response to the Output Sub-code.

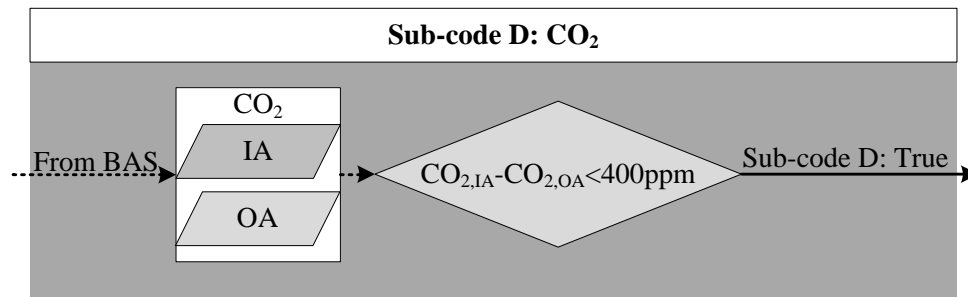


Figure 7 – Sub-code D: IAQ

3.5. Output Sub-code

The Output Sub-code is finally responsible for aggregating all of the responses from the first four sub-codes, A-D, and determining what ventilation mode the space should be in. The Output Sub-code, illustrated in Figure 8, checks if all of the sub-codes respond true, which means that conditions are favorable for HV. At this point the Output Sub-code will ensure that the control is not cycling, so once the HV Mode has been cancelled, it cannot be re-enacted for a fixed amount of time (arbitrarily set as an hour in Figure 8). If all of these conditions are met, the program will signal the BAS to operate in HV Mode, otherwise the space will operate in TMV Mode. In HV Mode, the BAS will actuate mechanical components related to HV (e.g., setback AHUs and open windows). In the next sections, this automated control will be verified through computer simulation. There will also be more discussion about how to determine the best way to operate the system through the case study commissioning example. As stated in the objectives, this research departs from industry standards by focusing on implementation of the system rather than modeling the system to ensure its proper operation. Even if the system's operation has not been optimized through ventilation modeling, commissioning using the automated control can provide a means for economically determining an operation protocol for the HV system.

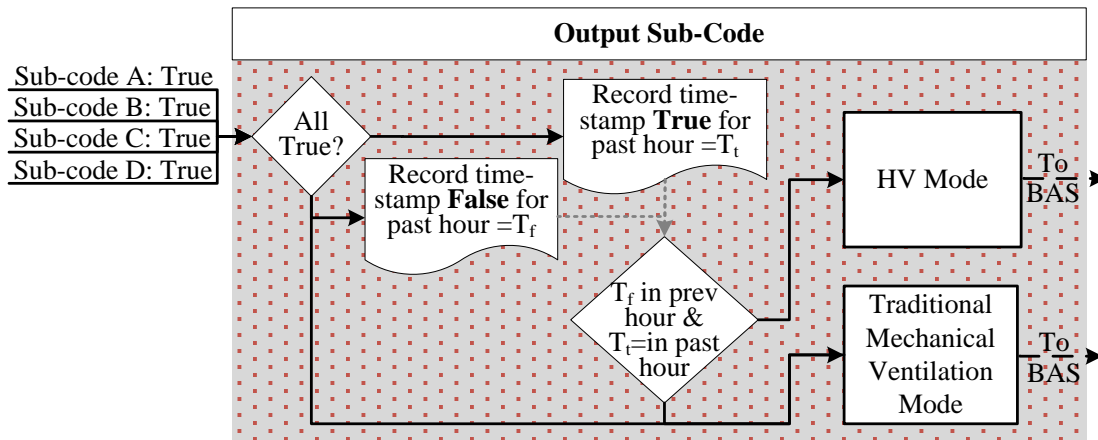


Figure 8 – Output Sub-code

4. Control Verification through Modeling

This automated control was simulated using weather data and AHU energy information from the Wisconsin Institutes for Discovery over the course of the 2011 summer cooling season (i.e., June-September) in order to verify its performance. This automated control was used to determine the best approach to operate the HV system at the Wisconsin Institutes for Discovery without resorting to a complex computational fluid dynamics model. Since a ventilation model was not used, dynamic internal conditions could not be modeled (e.g., energy use impacted by using HV, or internal temperature conditions affected by opening the building to the environment). Therefore, internal conditions specific to the building could not be verified through computer simulation, but this aspect was validated through the integration of the control into the case study building.

4.1. Case Study – The Wisconsin Institutes for Discovery

The Wisconsin Institute for Discovery at the University of Wisconsin – Madison’s campus, is a \$213 million research laboratory that was funded by public and private investors and completed in December 2010. This facility is located in a humid-continental climate, and houses biomedical, chemistry and computing researchers in its 4 story 33,000 m² footprint. The basement serves as a support space while the top three floors house nine wet laboratories. These bio-safety level laboratories require complex mechanical systems to relieve researchers of possible contaminants through fume hoods, enhanced filtration of circulating air, and ventilation. The ground floor, referred to as the Town Center, is open to

the public with conference rooms, study areas, a café, dairy bar, and restaurant covering an area of 4800m². This public space may be opened to the outside environment through operable windows, wall partitions and atria louvers, and is separate from the laboratories as shown in the cross sectional view of the building in Figure 1.

The Wisconsin Institute for Discovery is an ideal example of a complex building that has the potential to utilize HV in spaces that do not require strict ventilation, such as the Town Center shown in Figure 9. While the building had the ability to use HV in the public space prior to this research, no operations strategy had been developed and implemented as part of the building operation protocol. Additionally, no airflow or computational fluid dynamic model had been created to optimize the HV control and operation, so the building manager was left to develop a method for operating the system.

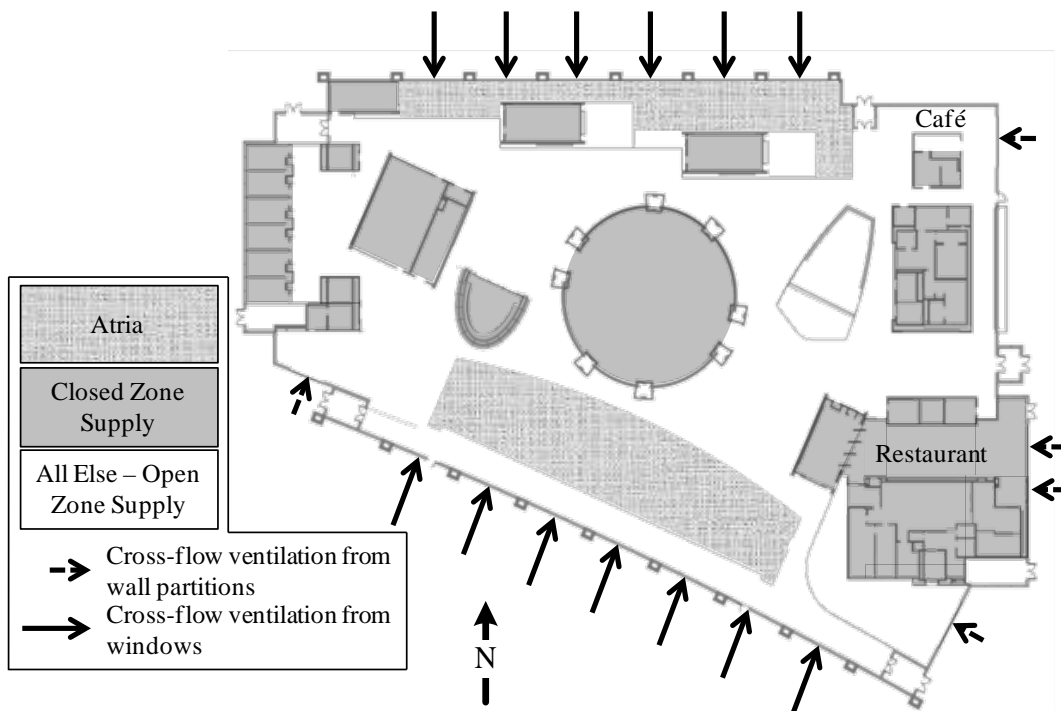


Figure 9 – Town Center HV Plan

Two AHUs, separate from the mechanical systems for the laboratories on the top floors, service the Town Center. The Town Center AHUs are variable-air-volume systems with economizers, cooled with campus-provided chilled water, and controlled through a BAS. Control actuated windows and operable wall partitions promote cross-flow ventilation allowing air to flow through the public space (shown in

Figure 9 as open zone supply) and buoyancy driven ventilation is aided by two large atria that are separated from the laboratories on the top floors by a glass façade (shown in Figure 1). Stack effect hot air is exhausted through louvers in the ceiling of the atria. This phenomenon can be mechanically assisted by fans located at the roof of the atria. While most of the public space can be ventilated through these combined natural ventilation measures, Figure 9 details some areas that do not have direct access to outside ventilation (shown as closed zone supply) requiring TMV even when HV is implemented throughout the rest of the floor.

4.2. Computer Simulation

The automated control developed in this research was modeled using a computer simulation to verify its logic. The goal of this simulation is to verify that the automated program would initialize HV Mode when external conditions allowed for it. The simulation was used to illustrate potential energy savings if HV was actually used over the course of the 2011 summer cooling season in Madison, WI. The inputs for the simulation are external conditions including temperature, humidity, and air pressure obtained from a weather station located on a nearby building. Other inputs include the energy consumption data for the AHUs operating under TMV as shown in Figure 5 and obtained from the BAS.

The simulation then incorporated the logic outlined in the automated control. The simulation consisted of numerous if-then-else loops checking the criteria set for each sub-code. Since the model was limited to data provided from external conditions and AHU energy data from BAS, some criteria had to be assumed to be able to test the HV operation in the building. First, T_{IA} was set to a constant value (20°C) that would always be within the comfort range so the only temperature criterion that had to be met was T_{OA} . Secondly, this model assumed that when the space operated in HV Mode, the energy consumption would be 56 percent of that calculated for a particular period as a previous study found this to be the average savings expected in this particular space [15]. Finally, IAQ criterion was assumed to be within acceptable range since no CO₂ sensor data was available for this simulation.

The automated control's computer simulation outputs energy consumption of the AHU using data from Table 2 and Eq. 7. It also outputs the predicted energy consumption of the AHUs if TMV was to be

used from the regression model. Finally, the simulation outputs the ventilation state of the Town Center (i.e., either HV Mode = 1 or TMV Mode = 0).

The statistical, open-source package R was used to generate the linear regression model of the energy use (E_{AHU}) as a function of parameters that were not originally used to calculate this value in Eq. 7. These parameters were collected throughout the study period (i.e., 6/1/11 – 9/20/11), and included day-of-week, time-of-day (hour), OA temperature (T_{OA}), OA relative humidity, OA enthalpy, and atmospheric pressure. The statistical analysis established a strong correlation between AHU energy use (E_{AHU}), and T_{OA} and hour. When these variables were considered, day-of-week, OA relative humidity, OA enthalpy, and atmospheric pressure did not significantly impact the model (i.e. p-values were greater than 0.05). T_{OA} and hour were used to produce the linear regression model shown in Eq. 8. The AHU energy use is denoted by $E_{Regression}$ in this equation to distinguish it from the actual AHU energy use (E_{AHU}) calculated in Eq. 7. This model fits the data with an adjusted R^2 value of 0.689, and residual standard error 25.84 on 2,180 degrees of freedom.

$$E_{Regression} = 189.8 - 34.74T_{OA} + 2.35T_{OA}^2 - 0.04T_{OA}^3 + 4.06hour - 0.03hour^2 - 0.04hour \times T_{OA} \quad \text{Eq. 8}$$

Figure 10 provides an excerpt of these outputs documenting when the automated control advises the space to operate in HV Mode and prints actual energy use in comparison to the regression model. When the space enters HV Mode, there is a substantial reduction in Actual Energy Use in comparison to the Regression Model Energy, especially throughout periods of the day when AHU energy consumption is typically highest.

The simulation was completed for the entire cooling season and the system performance was analyzed. The results from this model have shown that facility managers can expect substantial energy reduction when operating HV in public spaces of complex buildings. Considering this case study's summer weather patterns and building loads, the system could have been operated for 372 hours of the 1343 hours (day and night) between June and September or 27 percent of the time. Using HV when possible, in comparison to the actual mechanical ventilation energy consumption of the Town Center, would have resulted in a total savings of 6,353 kWh, or approximately 20 percent of the energy used

during the 2011 summer cooling season. While this model is specific to the case study, the automated control program developed for this particular system is able to be generalized to many HV systems and its implementation is described in the commissioning methodology.

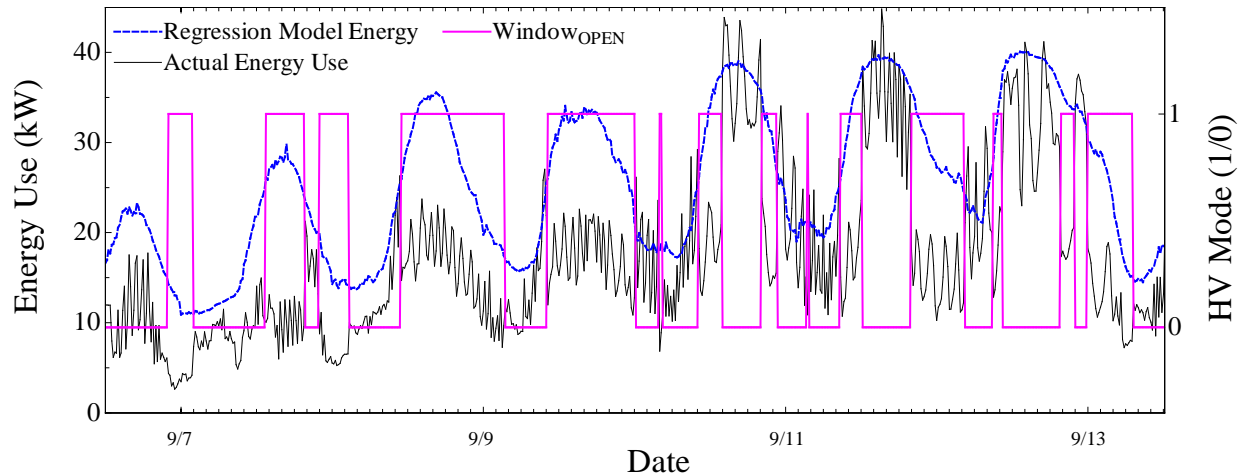


Figure 10 – Plot of AHU energy use when HV is utilized for a sample week (Sep. 2011)

5. Hybrid Ventilation Commissioning Methodology

The automated control developed through this research was implemented in a commissioning methodology of the case study building. This process ensures that the criteria for each sub-code established in the control are appropriate for the space and application. The methodology also provides a means for testing the installed HV system to determine the best way to operate it. Thus far, the outlined control only provides a signal for the space to operate in TMV Mode or HV Mode. Another sub-routine then actuates HV mechanical components (e.g., window and atria louvers) when the space enters HV Mode as described in Section 5-2.

The objective of the commissioning methodology is to verify thermal comfort set points and, through analysis, identify the best way to operate the HV system. When the space enters HV Mode as determined by the automated control, a sub-routine actuates HV components (e.g. windows, louvers). These components are actuated in series and referred to as a HV strategy. The automated control is only responsible for determining when HV should be used, and commissioning determines which strategy should be used for a particular space through testing. The best operation strategy was selected on the

criterion of average energy savings calculated from the automated control program while ensuring thermal comfort and IAQ requirements are met.

Figure 11 illustrates the framework adopted in this study. The methodology begins by integrating the automated control discussed in the previous section into the BAS (Phase I). The second phase focuses on determining which HV components and strategies to test, how those strategies were implemented through a testing matrix, and how each control was developed. In Phase III, the automated control was tested to verify that the set-points or criteria for each sub-code were appropriate for the application. Phase IV, in conjunction with Phase III, was also used to track energy savings of different HV operation strategies to determine which strategy performs best in the space.

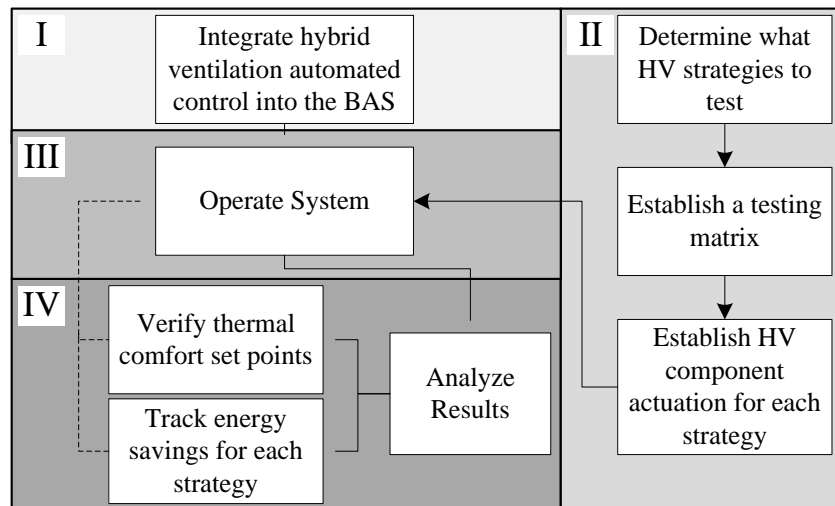


Figure 11 – Commissioning Methodology for HV

5.1. Phase I

The first step in the methodology was to incorporate the automated control into the BAS. HVAC operation was controlled by a Johnson Control’s Metasys System, and this system has a graphical programming language, which was used to develop a control similar to that described in Section 3.

The commissioning methodology relies on the BAS to eventually actuate HV components through direct digital control if the space enters HV Mode. The automated control could be used even if there is no digital control of these components; however, it will be more difficult to track how the system is being operated through manual control and the operation’s subsequent performance. In this case, the building

could use a signaling system to alert building operators that conditions are ideal for HV and that TMV has been setback. This leaves the presumption that building operators and occupants will respond when a space enters HV mode, which may not be appropriate in some areas such as public spaces where occupants are mostly transient. In this case study the BAS directly controls all components associated with the HV.

5.2. Phase II

Phase II establishes what dynamic building components are associated with HV operation. This study considered several scenarios and established three strategies that actuate different HV components found within the Wisconsin Institutes for Discovery. To illustrate these strategies, Table 2 outlines a testing matrix that describes how components and strategies interact. Components, denoted with alpha characters (e.g., A. Windows or Louvers) are identified at the header of the table. The rows of the table detail the strategy and what components are actuated. The Building Base Case Strategy references what state each component is in under TMV, which is the base case scenario for energy savings comparison. Component actuation is then identified with bold text as OPEN/CLOSED or ON/OFF. While this list is not exhaustive, it does represent a number of HV components typically found in commercial buildings.

Table 2 – General testing matrix for hybrid ventilation strategies

Test Strategy	A. Windows or Louvers	B. AHU Open Zone Supply	D. Atria Louvers	E. Mechanical Assist Vent Fans
0 – Building Base Case	CLOSED	ON	CLOSED	OFF
1 – Base Case HV Strategy	OPEN	OFF	CLOSED	OFF
2 – HV Strategy 2	OPEN	OFF	OPEN	OFF
3 – HV Strategy 3	OPEN	OFF	OPEN	ON

The Base Case HV Strategy requires minimum component actuation, and focuses on using cross-flow ventilation through only operating the windows and turning off air conditioning to the Open Zone Area. Open zone supply refers to areas within a space that have access to exterior windows or louvers (as shown in Figure 9). All other HV strategies actuate these two components (i.e., windows **OPEN** and AHU open zone supply **OFF**). Strategy 2 is an extension of Strategy 1 by opening atria louvers to allow warm air to exhaust from the atria thus utilizing stack effect. Finally, Strategy 3 extends Strategy 2 by utilizing the

mechanical assisted vent fans to enhance stack-effect ventilation through atria louvers.

The control initialization occurs when the automated control identifies favorable conditions for HV Mode. A sub-routine then carries out HV actuation. Figure 12 illustrates the sub-routine used to actuate HV components and explains the control strategies defined from the rows of Table 2. This figure details what components actuate when the space enters HV Mode. First, in accordance with Strategy 1, windows open and open zone supply turns off. Then, to operate Strategies 2 or 3, the other HV components would be commanded to actuate. Since each strategy is a modification of the others, this process is fairly simple, and testing each strategy could then highlight the best strategy to use on a permanent basis in the building.

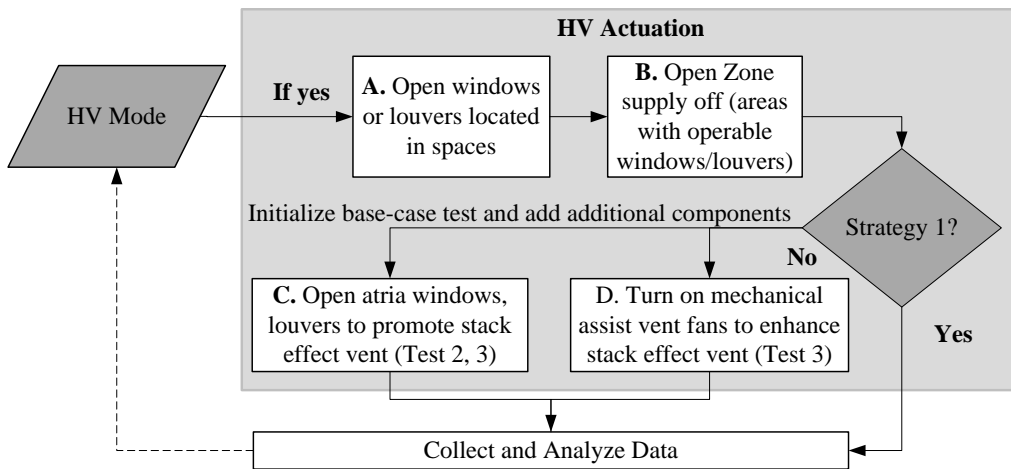


Figure 12 – Varying control strategies based on Test Matrix

5.3. Phase III and IV

Once the automated control was implemented into the BAS, the automated control was allowed to operate. Phases III and IV are completed in concert as the system is continuously commissioned when it is operational. The automated control was first allowed to operate for one month from 3/15/12-4/23/12 without actually allowing the sub-routine to actuate HV components when the space changed modes from TMV to HV. In this way, each sub-code could be monitored to ensure that the system was operating as anticipated. Some criteria related to temperature and humidity had to be modified for the particular application so that HV Mode would take place more often. For example, increasing the range of operating temperatures (while ensuring occupant comfort) allowed the HV system to operate for longer periods of

time. When the sub-routine was eventually allowed to actuate components, these modifications were tracked by having occupants in the space complete comfort surveys to ensure that thermal comfort was being met.

Once the performance criteria for each sub-code had been evaluated, the automated control was used to test each of these strategies in the building. A previous study used a generic testing matrix and operated the strategies manually before the automated control was complete. This study took place over the course of two weeks (9/28/11-10/10/11), and Table 3 outlines the energy savings results of the study [15].

Table 3 – Hybrid Ventilation Test Results

Test Strategy	Hours Tested	Average Savings from Baseline
1 – Base Case HV Strategy	21	42.09 %
1 – Base Case HV Strategy at Night	6	33.20 %
2 – HV Strategy 2	21	56.58 %
3 – HV Strategy 3	10	51.54 %
3 – HV Strategy 3 at Night	6	26.66 %

This study found that Strategy 2 from Phase II performed the best in comparison to the TMV regression model developed for the building with an average energy savings of 56 percent [14]. This strategy was initially instrumented in the building. However, it was discovered through operation that mechanical assist vent fans had to be running in order to promote stack effect. Therefore, Strategy 3 was implemented which included the operation of variable speed fans where the initial study set the fans to operate at 25 percent capacity.

There was uncertainty in the best speed to operate fans ranging from 0-100 percent. This provided researchers the opportunity to establish different strategies as discussed in Phase II in order to test which strategy worked best in the space. Strategy 3 was considered by having fans at 5 percent, 50 percent and 100 percent of full capacity. Commissioning the HV system within the Wisconsin Institutes for Discovery is ongoing, and the plan forward is to test each of the strategies over the course of the cooling season. These strategies will be implemented in the sub-routine that takes effect when the automated control determines the space should operate in HV Mode. Each strategy will be tested within the space over the course of a month capturing a variety of internal and external conditions. The energy savings calculated

by Sub-code C will then be used to determine which strategy works best. Future research will continue monitoring the progress of the commissioning of the Wisconsin Institutes for Discovery, and other case studies will be sought to validate the commissioning methodology for hybrid ventilation established in this research.

6. Conclusions

This research has shown that hybrid ventilation can provide substantial energy savings in complex buildings through automated control. The research details an automated HV control for complex buildings that can be generalized to other commercial building applications. More importantly, this research provides designers, engineers, and building managers with a commissioning methodology which can be used to implement an automated control for HV and determine the best way to operate the installed system. This research departs significantly from previous studies and industry standards by focusing on implementation of the system rather than modeling the system to ensure its proper operation. This is important when considering buildings with installed systems or retrofit systems that do not have a ventilation model created to detail operation. Even if the system's operation has not been optimized through ventilation modeling, commissioning using an automated control can provide a means for economically determining how to operate HV within the space.

7. References

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1. Appendix A – Measurement Devices and Specifications

1.1. Sensor Location

1.1.1. *Hybrid Ventilation Sensors (.xlsx)*

1.1.2. *Sensor Locations (.pdf)*

1.2. Sensor Specifications

1.2.1. *AHU Sensors (.pdf)*

1.2.2. *Zone Sensors (.pdf)*

2. Appendix B – Hybrid Ventilation Testing Notes

2.1. *Testing Modules (printed, .docx)*

2.2. *Anecdotal Testing Notes taken from 9.20.11-10.10.11 (printed, .txt)*

2.3. *Comfort Surveys (printed, .docx)*

3. Appendix C – Air-handling Unit Energy Calculations

3.1. *AHU Energy Raw Data (.xlsx)*

3.2. *EES Source Code (printed excerpt for Mezzanine AHUs, two .ees files and two .lkt files)*

4. Appendix D – Regression Analysis

4.1. *Weather Data (.csv)*

4.2. *EES Source Code (printed excerpt for Mezzanine AHUs, two .ees files and one .lkt file)*

4.3. *R Analysis (excerpt of R code printed, .csv and .R)*

4.4. *Regression Analysis Raw Results (explanation of each analysis provided, .xlsx)*

5. Appendix E – Indoor Comfort Standards

5.1. *Wisconsin Institutes for Discovery Design Goal (printed, .pdf)*

5.2. *Adaptive set point (established through ASHRAE, calculated using EES) (printed, .ees)*

5.3. *Wisconsin Institutes for Discovery humidity and temperature set points (printed, .xlsx)*

6. Appendix F – Automated Control

6.1. *Automated Control Simulation (printed, .ees)*

6.2. *Automated Control Anecdotal Notes (printed, .docx, .txt)*