Abstract

Variable air volume (VAV) systems have historically been designed following methods that result in excess energy consumption and inadequate ventilation. Designing VAV systems using heating and cooling design days and following the ASHRAE 62.1-2010 Ventilation Rate Procedure is shown to be inadequate for its intended purposes. A method for quantifying energy and ventilation performance using dynamic energy simulations is coupled with a genetic algorithm to optimize VAV terminal box minimum positions and central outside air damper minimum position. The genetic algorithm results in improved energy performance while simultaneously addressing concerns for underventilation, as shown in a case study medium office archetype energy simulation. The method provides an opportunity to improve energy consumption and indoor air quality in the existing building stock without requiring extensive capital retrofits or complex controls algorithms.

Key Innovations
- Quantification of ventilation using dynamic energy simulation
- Optimization of energy and ventilation performance with high-fidelity terminal box setpoint design

Practical Implications

Industry standard practice for ventilation design may not always provide adequate ventilation rates. Quantifying the ventilation performance using dynamic energy simulations allows the optimization of designs for both energy and ventilation. Selecting individual terminal box setpoints allows significant energy and ventilation improvements over an across-the-board selection.

Introduction

The background and motivation for this research is presented below. First, multi-zone central variable air volume (VAV) air handling units are introduced, then the industry standard method for specifying ventilation rates is described. Next, research trends on the competing objectives of indoor air quality and energy consumption is discussed. Finally, the academic contributions of this research are defined.

VAV Systems

Multi-zone central variable air volume (VAV) air handling units are the most commonly installed HVAC system in North American commercial and institutional facilities (Taylor, 2018; Zhang et al., 2013). Simple VAV systems are comprised of a central air handling unit that is usually equipped with a variable-speed fan, heating and cooling coils, and a mixing box to maintain the air flow rate, the temperature, and ventilation, respectively. Downstream of the central unit, VAV terminal boxes maintain space temperatures by modulate dampers to vary the supply of air.

The mixing box is a set of dampers that modulate to mix return air from the occupied spaces with outside air for ventilation. Supply air temperature setpoints are set cold relative to the occupied space setpoints regardless of operation, usually at 13°C. When outside conditions are favourable the mixing box will increase the proportion of outside air to reduce cooling energy; referred to as air-side economizing. The outside air damper will have a minimum damper position setpoint such that adequate ventilation is maintained.

Terminal box dampers are likewise programmed with a minimum box position so that during periods of low loads—and therefore low airflow—there remains adequate ventilation air. Minimum box position setpoints have historically also served the role of addressing concerns that occupants feel ‘stuffy’ at a lack of adequate air movement, or feel ‘drafty’ from cold air ‘dumping’ due to a lower diffuser throw at lower air-flow rates (Arens et al., 2015). Terminal boxes can be equipped with heating coils to prevent overcooling or to provide supplemental heat as required, and are referred to as reheat boxes.

VAV terminal boxes can be classified as pressure dependent or pressure independent. Pressure indepen-
dent boxes are installed with airflow measuring devices that directly calculate the amount of air passing through the box. Pressure dependent boxes do not measure the airflow and simply modulate the damper to meet thermal loads. The amount of airflow as a function of damper position is non-linear and dependent on the relative pressure in the upstream ductwork. Newer VAV terminal boxes are more likely to be pressure independent than older boxes.

Older building automation systems (BAS) are simply collections of independently operating control hardware. Zone-level and system-level equipment on older systems do not have the capability to communicate with each other or be controlled by a central algorithm. These legacy systems lack the ability to be upgraded with some of the newer, more complex, algorithms needed for building-wide optimized operation.

**Ventilation Rate Procedure**

The most commonly followed design process for ensuring adequate ventilation from a VAV system is the Ventilation Rate Procedure (VRP) from ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality, section 6.2 (Persily, 2015). The standard requires that an adequate amount of outside air is supplied to the breathing zone by the VAV ‘delivering no less than the minimum ventilation rates required whenever the zones are occupied’. The minimum ventilation rate specified by ASHRAE 62.1 VRP is a summation of a floor area-based rate and an occupancy-based rate (ASHRAE, 2010). The VRP is a calculation procedure where a critical zone is determined based on worst-case conditions which define the system ventilation efficiency and required outside air rate. The standard does not dictate to the designers how to select worst-case conditions, but standard practice has been to analyze the system at cooling and heating design days during occupied periods (Abramson and Wong, 2011; Hudson, 2007).

ASHRAE 62.1 also does not dictate a terminal box minimum position, however, ASHRAE standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings, stated that ‘the minimum airflow for the VAV reheat boxes should be set to 30% of the zone peak supply air volume or the outside air ventilation rate, or the airflow rate required to comply with applicable codes or accreditation standards, whichever is larger’. While the Standard revised the minimum from 30% to 20% in 2013 (ASHRAE, 2013), setting the minimum boxes to 30% is the default and standard practice for equipment manufacturers, and it can be assumed that most of the existing building stock follows this default (Abramson and Wong, 2011; Hudson, 2007).

**New research on VAV box minimums**

HVAC designers use data sheets from equipment manufacturers and guidelines to design their systems. Manufacturers give an acceptable VAV box damper control range, typically being a 30% minimum. This default is then carried onwards for design, installation, and commissioning of systems. ASHRAE RP-1353 (Liu et al., 2012) tested a number of VAV boxes from popular manufacturers at a range of operations and found that most VAV boxes are suitably accurate down to approximately 5% damper position.

Within the HVAC design community, it is commonly assumed that a minimum amount of airflow within spaces is required to properly mix air. This eliminates cool air ‘dumping’ at low airflows and reduces ‘stuffy-ness’ within zones. ASHRAE RP-1515 (Arens et al., 2015) identified that those assumptions are baseless. Feeling ‘drafty’ is more likely from overheating caused by minimum box positions set too high, and feeling ‘stuffy’ is correlated with overheating and not ventilation rates. The researchers found that reducing the minimum box positions to around 10% to 20% actually increased the thermal comfort of the occupants and reduced energy consumption by approximately 14% in a case study building.

Fernandez et al. (2017) identified that retuning the minimum VAV box damper setpoints is the most effective control measure for medium and large commercial buildings. They estimate that on a per-building basis a site energy reduction of approximately 15% is possible, and nation-wide retuning of minimum damper setpoints could reduce national site energy consumption by over 6%. In addition, Fisk et al. (2012) estimate that the economic benefit of improving ventilation in the existing American building stock is potentially 40 billion USD per year.

**Competing Objectives of Energy and Indoor Air Quality**

Providing adequate fresh air to occupants of the built environment provides numerous health benefits and can significantly reduce the likelihood of the ‘sick building syndrome’ (Chenari et al., 2016). Indoor air quality can be modelled as a balance between source contaminant generation rate and ventilation dilution. Numerous challenges and uncertainties associated with contaminant source control has lead to ventilation being the main method in maintaining indoor air quality (Emmerich et al., 2017). Conditioning outside air, however, can be one of the largest energy expenditures in operating buildings. This leads to an obvious tradeoff between energy consumption and indoor air quality.

There have been a number of studies that have investigated the tradeoff between energy and indoor air quality for central VAV systems. Yu-Pei et al. (1997) studied eight ventilation methods to quantify energy consumption (using a set of polynomial models in conjunction with BLAST models), and ventilation performance (using maximum CO₂ as the indoor air quality identifier). Zhang et al. (2013) quantified the
potential energy savings of using advanced occupancy sensors to control both the zone lighting and operation of terminal boxes. Kusiak and Li (2009) used the maximum CO$_2$ in a space as a proxy for indoor air quality while optimizing an equipment’s on/off schedule. Dai et al. (2014) and Ben-David et al. (2019) used productivity models to convert indoor air quality and thermal comfort into an annual dollar value for optimizing ventilation rate and space temperature.

Mofidi and Akbari (2016) and Nassif et al. (2005) both integrated a multi-objective algorithm directly into the HVAC control system to trade off ventilation and energy consumption. Zhou and Haghighat (2009) developed a surrogate model to replace high-fidelity CFD models to optimize ventilation, thermal comfort, and energy consumption, using maximum CO$_2$ concentration as the identifier for indoor air quality.

**Novelty of Research**

To quantify indoor air quality performance, researchers tend to use either maximum CO$_2$ concentration in occupied zones or a productivity model. CO$_2$ concentrations have been proven to be a poor choice as indication of indoor air quality (Emmerich et al., 2017). In fact, the use of CO$_2$ is likely an artefact from historical versions of the ASHRAE 62 standard (Persily, 2015). There is ongoing debate and further research required to fully understand the impact of ventilation on human comfort and health; however, there is strong evidence to suggest that underventilating below the minimum requirements in ASHRAE 62.1-2010 has a significant negative impact on occupant health and contributes to the sick building syndrome (Godish and Spengler, 1996; Chenari et al., 2016; Persily, 2015). Recent research has found a potentially quantifiable economic impact of inadequate ventilation; however, further research is recommended before it is generally applicable (Chenari et al., 2016).

None of the studies on different control strategies or building optimization have considered the selection of VAV box minimums. Recent research has trended towards increasingly complex control algorithms and requires additional sensors located in each zone. These studies do not address the large existing building stock that can not implement these algorithms without extensive upgrades to their control systems (Png et al., 2019). In addition, the requirement for additional sensors located in all zones may significantly increase the amount of intrusive maintenance in order to ensure proper operation of the HVAC systems (Schell, 2001). Finally, there should be a preference for simpler control systems: a large study on high-performance UK buildings has identified complex controls systems as a major contributor to the performance gap (Palmer et al., 2016). The solution presented in this research is mainly applicable to improving the performance of the existing building stock, which likely do not have the capability to extend their control systems to include the novel higher performance control algorithms.

This paper addresses these issues in the field of optimizing the tradeoff between indoor air quality and energy consumption in two separate ways.

1. Quantification of indoor air quality performance relative to an ASHRAE 62.1-2010 baseline, along with quantifying the variation in underventilation following industry standard practice.
2. Quantifying the relative improvement in both energy consumption and underventilation a case study energy model based on an archetype building by using a genetic algorithm to retune the setpoints for terminal minimum box positions, along with a comparison to a base case following the standard ventilation rate procedure method.

The model, methods, and results are made publicly available$^1$.

**Methods**

The methods used to calculate and optimize the energy consumption and ventilation performance are documented below. First the dynamic simulation case study is presented, followed by the procedure for calculating ventilation performance, and finally the genetic algorithm for multi-objective optimization is described.

**Dynamic Simulation**

An EnergyPlus model is used to simulate the energy consumption of a building over a year. The building is a medium office, based off of the DOE medium office archetype (Duru et al., 2011), and modified for use with the Net-Zero Navigator project (Westermann et al., 2020), shown in Fig. 1. The building is simulated with the CWEC 2016 Victoria, BC, Canada weather file. The building is equipped with a single central VAV providing supply air at a constant temperature setpoint of 13°C to VAV terminals located in each zone. The terminal boxes are equipped with hot water reheat coils that allow a maximum of 30% airflow or the minimum box position, whichever is larger, during heating.

Airflow rate through dampers is simplified as being directly proportional to damper position, and is independent of upstream or downstream pressure effects or non-linear damper behaviour. The minimum airflow rate through a damper is therefore equal to the minimum damper position multiplied by the nominal airflow.

**Ventilation Calculation**

Ventilation calculations follow ASHRAE 62.1-2010 Ventilation Rate Procedure (VRP). For each hour of the year a minimum specified amount of outside air

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$^1$https://gitlab.com/KCant/ventilation-study.git
ASHRAE 62.1-2010. Design occupancy is 25 m² required ventilation rates used in the simulations follow its floor area and occupancy. The occupancy and required to be supplied to each zone depending on archetype.

For the base VRP scenario, the design process is as follows: the minimum damper position is predetermined for the terminal boxes and the simulation is run for the heating and cooling design days. For each time step in the simulation the VRP from ASHRAE 62.1-2010 section 6.2.5 is completed to calculate the central outdoor air damper position required. The highest required damper position across the design days is recorded and set as the central minimum outdoor air damper position for the simulation.

**Genetic Algorithm**

The proposed procedure emulates the multi-objective optimization described in Papadopoulos and Azar (2016), linking EnergyPlus with Python via the be-sos (Christaannse et al., 2021) suite, which connects the Eppy library (Philip, 2016) to the Platypus optimization library (Hadka, 2015) using a number of Python helper functions.

A multi-objective optimization (MOO) genetic algorithm (GA) is used to optimize the performance of the building. The objectives in the MOO are to minimize the energy consumption and the amount of underventilation. Each of the 15 terminal boxes in the building are allowed a unique minimum box position, ranging from 0% (fully closed) to 100% (fully open). The MOO algorithm used is NSGA-II (Deb et al., 2002)².

**Results**

The results of the simulations and optimization are presented. First, the benefits of quantifying ventilation performance using dynamic simulations is shown. Next, the potential improvements of using a genetic algorithm to optimize minimum box positions is compared to the traditional approach.

**Quantifying Ventilation Performance Using Dynamic Simulations**

Table 1 displays the minimum outdoor air damper position, annual energy consumption, and underventilation for each set of minimum VAV box terminal positions (in 10 Energy consumption ranges from 125 ekWh/m² to 198.6 ekWh/m², and underventilation ranges from 0.5% to 2.8%. In particular, the industry default value of 30% across all zones is of interest, which results in a minimum VAV central outdoor air damper position of 43% and 1.2% underventilation.

None of the solutions following the VRP technically meet the requirement that ventilation systems must be capable of delivering the minimum ventilation rates at all occupied hours of the year ASHRAE (2010). This is based on the interpretation that ‘capable’ includes actual hourly operation due to the designed setpoints, thermal loads, occupancy, and control algorithms.

When the central outdoor air damper minimum position is included as an additional parameter, the resulting solution space is expanded to include potential design selections that either reduce the amount of underventilation, reduce the annual energy consumption, or simultaneously reduce the energy consumption and underventilation.

²For this case study, the population size is set to 100 and run for 10 generations, following the standard rule-of-thumb of a 10:1 ratio of population size to generations. Crossover and mutation operators and settings remained as the default platypus settings. The optimization algorithm is only run once and therefore no guarantee of true optimality is reached; however, the results provide a clear basis of discussion and show an improvement over standard practice. It is assumed that industry uptake of the method would not require convergence of absolute optimality.
Optimizing Energy and Ventilation by Selecting Minimum Box Position on a Zone-By-Zone Basis

The GA enabled the optimization of terminal box minimum position on a zone-by-zone basis simultaneously with the central outdoor air damper minimum position. The resulting pareto-front of nondominated solutions shown in Fig. 3 improved both the ventilation and energy performance of the case study building. Assuming 30% default minimum box positions and ensuring no underventilation would require a central outdoor air damper position of 80% to 90% and an energy consumption of 141.9 to 146.3 ekWh/m². The optimized design can achieve no underventilation and an energy consumption of 130.1 ekWh/m², a savings of 8% to 11%. Alternatively, the optimization results in a savings of 9% with no additional underventilation over the default minimum terminal positions (30%) and the VRP procedure.

Figure 4 presents the pareto-optimal results from the genetic algorithm. Minimum box positions mostly varied between 5% and 15% across the pareto front for east and west zones, 0% to 20% across the pareto front for north zones, 15% to 35% regardless of position on the pareto front for south zones, and between 5% and 55% for core zones. In addition, central outdoor air damper minimum position increased along the pareto front. For external zones, the optimal minimum terminal box positions rarely exceeded the default 30%, even when the focus was on minimizing underventilation, supporting recent guidelines to reduce terminal box positions below the default 30%.

The trends along the pareto front can be summarized as the most effective ways to reduce underventilation at the least cost to energy consumption.

Discussion

Quantifying ventilation using dynamic hourly simulations identified that seemingly equivalent VRP-compliant designs resulted in a range of annual ventilation performance. All of the seemingly compliant designs in this study do not technically meet the requirements of ASHRAE Standard 62.1-2010 Ventilation Rate Procedure due to periods of underventilation. If the requirement for adequate ventilation is to meet the minimum ventilation rate at any occupied period, designing the ventilation system based on a worst-case heating and/or cooling design day is not appropriate. The results of this research show that for a minimum box position of 30% set across all zones in this case study simulation, the required minimum outdoor air damper position would be 90%—a number HVAC designers would likely balk at—and would look to increase the minimum position of terminal boxes in critical zones in order to reduce the central outdoor air damper minimum position to a more conservative value. The resulting annual energy consumption would increase by over 7% compared to the standard VRP calculation.

If the VRP design method is deemed valid by the authority having jurisdiction, with minimum outdoor air damper position calculated according to the expected operation on heating and cooling design-days, and underventilation of the proposed designs varied from 0.5% to 2.9%, then that would suggest that the acceptable amount of underventilation is flexible. Improving ventilation can improve occupant health and reduce the prevalence of the widely acknowledged sick building syndrome. The impact of short periods of underventilation, however, requires further research.

The design solution presented can be considered a ‘sub-optimal’ solution because there are likely still hours where the minimum box position can be improved with dynamic control. A number of studies have been completed using highly intelligent control algorithms, including neural networks, genetic algorithms, and complex rule-based controls. These algorithms require large amounts of sensors to be placed in the controlled zones and building automation systems that are capable of communicating between terminal devices and central workstations for optimal control. There is evidence that commonly-used sensors, such as carbon dioxide sensors, are likely to drift out of calibration or fail. Additionally, existing commercial buildings would likely require an upgrade to their building automation systems in order to accept these new control algorithms.

Improvements from demand-control ventilation and highly intelligent control algorithms for VAV systems has been generally in the range of 5%-30% of total energy consumption. Energy savings shown in this case study for a mild climate (ASHRAE Zone 4C) are comparable to those in the literature for novel control algorithms that would require large capital upgrades to the existing buildings stock and ongoing calibration for the vast number of required sensors, whereas the implementation effort for this retrofit would be comparable to a re-balancing project.

Limitations and Future Research

There are a number of limitations to the research presented that require further development and research. The resulting setpoint selections in the study are not necessarily generalizable because they were only

<table>
<thead>
<tr>
<th>Min. Box Position</th>
<th>Min. OA Damper Pos.</th>
<th>Energy Cons. [ekWh/m²]</th>
<th>Underventilation</th>
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</thead>
<tbody>
<tr>
<td>10%</td>
<td>100%</td>
<td>134.2</td>
<td>1.3%</td>
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<tr>
<td>20%</td>
<td>46%</td>
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<tr>
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<td>40%</td>
<td>30%</td>
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<tr>
<td>50%</td>
<td>25%</td>
<td>174.7</td>
<td>0.7%</td>
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<tr>
<td>60%</td>
<td>22%</td>
<td>198.6</td>
<td>1.1%</td>
</tr>
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### Table 1: VRP Results

- **Min. Box Position**: Minimum box position on a zone-by-zone basis.
- **Min. OA Damper Pos.**: Minimum outdoor air damper position calculated according to the expected operation on heating and cooling design-days.
- **Energy Cons. [ekWh/m²]**: Energy consumption.
- **Underventilation**: Percentage of time with underventilation.

The GA enabled the optimization of terminal box minimum position on a zone-by-zone basis simultaneously with the central outdoor air damper minimum position. The resulting pareto-front of nondominated solutions shown in Fig. 3 improved both the ventilation and energy performance of the case study building. Assuming 30% default minimum box positions and ensuring no underventilation would require a central outdoor air damper position of 80% to 90% and an energy consumption of 141.9 to 146.3 ekWh/m². The optimized design can achieve no underventilation and an energy consumption of 130.1 ekWh/m², a savings of 8% to 11%. Alternatively, the optimization results in a savings of 9% with no additional underventilation over the default minimum terminal positions (30%) and the VRP procedure.

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Limitations and Future Research

There are a number of limitations to the research presented that require further development and research. The resulting setpoint selections in the study are not necessarily generalizable because they were only.
Figure 3: Energy and ventilation performance comparison of potential design options. A wide range of energy and ventilation performance is available for VAV terminal box minimum damper positions and central OA damper positions. Selecting each terminal box position independently can improve both energy and ventilation performance over the designs with a single minimum box selected across-the-board.

Figure 4: Details of the NSGA-II optimized designs. Different external load conditions result in different recommended terminal box setpoints. Designs with very low amounts of underventilation tend to be designs with core zones that have terminal box setpoints equal or above the default 30%, whereas all optimized designs have exterior zones with setpoints at or below the 30% default.
based off one case study simulation for a medium office building in a mild climate. In addition, airflow through dampers is simplified to not include pressure effects or non-linearities. This is especially important at minimum damper positions where the study assumes minimum damper positions result in a proportional percent of nominal airflow. Further, a common control strategy to reduce energy consumption is to reset the supply air temperature to warmer setpoints during colder ambient temperatures. An outside air temperature reset strategy may alter the impact of minimum box positions, and reduce the negative impact of higher box positions. Finally, the occupancy and internal loads in the case study building is deterministic which may not represent the actual occupancy of office buildings in use. Repeating the study for a number of different buildings, with different load conditions and space types in different climates, and with stochastic occupancy may result in more robust and generalized recommendations or guidelines.

The primary use-case for this method is the existing building stock with simple VAV systems controlled by legacy BAS equipment, in which revising the minimum box positions can be a more economical option to improve energy consumption and indoor air quality. This method, however, still requires the development of a detailed energy model and the optimization of setpoints. The relatively simple 15-zone model simulated in this case study required approximately 3 minutes per simulation. The genetic algorithm input 16 parameters and required 1,000 simulations for good convergence (although hypervolume calculations were not conducted to quantify convergence), with a total run time of under 4 hours with a 16-core processor. It is anticipated that larger, more complex buildings would results in increased simulation time and require a higher number of inputs. While the computation time increases substantially, the amount of effort saved relative to a manual design process is improved, and computational time is relatively cheap. Further improvements by replacing the dynamic energy simulation with a data-driven approach may reduce the design effort, and the use of more efficient optimization algorithms, such as Bayesian optimization, may reduce the computational burden.

Underventilation percentage is used as the metric for indoor air quality which quantifies how well the ventilation system performs compared to the minimum requirements of ASHRAE 62.1-2010, however, it does not give benefit to systems that provide additional ventilation above the minimum requirements. Additionally, it does not discriminate between large hours of small underventilation and small hours of larger underventilation. Further research is recommended to determine a more representative metric for quantifying ventilation performance.

Conclusion

VAV systems are the most prevalent HVAC system in medium and large commercial buildings. They have historically been designed using default terminal box minimum positions, based on incorrect assumptions, and following a design-day ventilation calculation procedure. This study used dynamic hourly simulations to quantify ventilation performance to facilitate the design of systems that have equivalent or lower rates of underventilation compared to the traditional Ventilation Rate Procedure required by ASHRAE 62.1-2010, while also reducing energy consumption.

The optimization algorithm NSGA-II was used to support the design process by providing insights into the tradeoff between energy and ventilation within a large parameter set of terminal box positions. The method employed in this research can help designers implement appropriate terminal box minimum positions for simple VAV systems that reduce energy consumption and potentially improve thermal comfort while addressing concerns of underventilation. The results presented using a case-study simulation building suggest that the standard practice for implementing the ASHRAE 62.1-2010 Ventilation Rate Procedure using cooling and heating design days may not provide adequate ventilation throughout the year.

References


Chenari, B., J. Dias Carrilho, and M. Gameiro da Silva (2016, June). Towards sustainable, energy-


American Society of Heating Refrigerating and Air Conditioning Engineers (2012). *Stability and Accuracy of VAV Box Control at Low Flows*.


