Evaluation of demand control ventilation impact on indoor air quality and energy efficiency of an office space in a tropical climate

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Abstract

Indoor air quality (IAQ) and energy efficiency are critical factors in the design and operation of office spaces. This study explores the transformative potential of Demand Control Ventilation (DCV) systems in optimizing IAQ and energy efficiency within office environments located in tropical climates. Unlike traditional ventilation mechanisms, which operate uniformly regardless of occupancy levels, thereby escalating energy expenditure, DCV systems dynamically adjust fresh air inflow based on real-time occupancy data. Through meticulous simulation analyses employing the Carrier Hourly Analysis Program (HAP), this investigation contrasts the performance of a conventional, constant ventilation setup against that of a DCV-modulated environment. This comparison utilizes actual occupancy, HVAC settings, and electrical loads. The findings reveal that DCV implementation not only upholds stringent IAQ standards but also heralds a significant reduction in average energy consumption by 38.9%. This study substantiates DCV's efficacy in enhancing IAQ and energy savings, positioning DCV as a cornerstone technology for sustainable retrofitting and design in tropical climates, and highlighting its potential applications in optimizing space ventilation systems.

1. Introduction

Ventilation is generally defined as the controlled exchange of air in a space with a mechanism to facilitate this exchange. The primary goal of ventilation is to maintain the chemical and physical state of the air while also meeting sanitary and hygienic requirements, that is, to ensure that certain meteorological parameters of the air are maintained [1]. Many studies have shown that inadequate ventilation rates have a substantial impact on health. According to [2], insufficient ventilation rates can cause hypersensitivity, allergies, lung infections, and sick building syndrome. Furthermore, [3] found that inadequate ventilation can cause the spreading of Covid-19 in aerosol conditions. With growing concern during the Covid-19 pandemic, some countries suggest that every building should increase its ventilation rate to reduce the spreading of Covid-19 [4]. In Malaysia itself, the Department of Occupational Safety and Health (DOSH) has published a guideline on how to increase building ventilation rate during the Covid-19 pandemic in order to increase effective dilution ventilation per person. According to [5], an optimized ventilation rate is not only suitable during the Covid-19 pandemic, but also would help workers to think clearly, increase workplace productivity and reduce the proportion of dissatisfaction with Indoor Air Quality (IAQ).

Apart from health issues, ventilation rates have a significant impact on energy consumption. Many studies have been done to control the ventilation rate to reduce energy consumption. Although there are numerous reports on energy reduction through the ventilation retrofit method, research on ventilation retrofit with the consideration of air quality is still lacking. Similarly, [6] stated in their study that ventilation retrofit with consideration of air quality is less frequently implemented because they are often regarded as energy-consuming methods. Despite the argument that improving indoor air quality would increase energy consumption, there are also significant results showing that improving IAQ can also reduce energy consumption. As mentioned by [7], with the right strategy, improving IAQ through ventilation optimization would also reduce energy consumption. [8] had introduced a ventilation control for a building, and the result shows good IAQ and is able to reduce 300 kWh/year in mild climates. Apart from that, [9] also mentioned that it is possible to reduce energy consumption whilst maintaining good IAQ by adopting an energy-efficient ventilation system. Moreover, [10] had proposed a proactive energy-efficient ventilation system at the train subway and the result shows significant energy reduction and improved IAQ.

One of the methods to control the ventilation rate is by using demand control ventilation (DCV). DCV is a control system that regulates the rate of fresh outdoor air entering the Heating, Ventilation, and Air Conditioning (HVAC) system in response to the actual demand for ventilation [11]. Compared to a constant air volume (CAV) ventilation system, application of DCV can reduce energy consumption, particularly from fan operation and cooling of fresh outdoor air [12]. Even though DCV can result in lower energy consumption by optimizing the ventilation rate, this strategy may result in lower indoor air quality (IAQ) with corresponding adverse health effects if indoor air quality parameters are not considered [13]. Given the negative impact of insufficient ventilation rate on occupant health, it is worthwhile to investigate the impact of ventilation rate optimization on the IAQ and energy consumption, particularly in office spaces. Resolving these issues is crucial because employees spend one-third of their waking hours in office spaces, making air quality critical for working conditions. Therefore, this paper aims to evaluate the impact of DCV on the indoor air quality in an office space and the energy savings achieved through the utilization of DCV on the HVAC system. This paper is organized as follows: Section 2 describes the ventilation rate relationship with energy efficiency and CO_2 concentration. Section 3 describes the case study of the IAQ and energy consumption analysis in an office space. Section 4 describes the utilization of DCV in the office space for energy efficiency and IAQ improvement. The findings and conclusions of the study are presented in Section 5 and 6.

2. Ventilation Rate relationship with energy efficiency and CO concentration

Ventilation is the process of introducing outside fresh air into a building space. In an HVAC system, ventilation air is usually heated, cooled, and dehumidified, depending on the weather conditions [14]. As a result, ventilation air consumed a significant amount of HVAC energy usage. According to [15], maximum ventilation rates, or the amount of fresh air delivered by the Air Handling Unit (AHU) are proportional to the maximum design occupancy of the building. Even though the space is only partially occupied, the actual occupancy rarely reaches the maximum design occupancy. It is not uncommon for an AHU to continually operate at the maximum ventilation rate, and this issue frequently leads to excessive ventilation, resulting in higher than necessary energy consumption [16].

Building spaces do not always need to have 100% fresh air. The demand for fresh air should vary according to the number of people in a building space at any one time. When there are fewer people in a building, the need for fresh air may be reduced. According to [17], DCV is a way of introducing varied amounts of fresh air depending on actual occupancy patterns. The mechanism allows the rate of ventilation to be adjusted constantly and automatically. The control is essentially performed by the use of sensors that respond to changes in occupancy. The output of the sensor is fed into a control device that regulates the AHU damper, which controls the pace of outdoor airflow through the ventilation system to ensure consistent air quality.

People would continuously exhale CO_2 during working, walking or even resting. The amount of CO_2 produced would be increased proportionally to the number of persons in a space. According to [18], a high CO_2 level in a room (> 1000 ppm) suggests insufficient ventilation and low levels of CO_2 (< 600 ppm) according to [19] may indicate that the ventilation rate could be reduced while maintaining good IAQ and reducing energy consumption. Many studies on human perception have been conducted to determine the relationship between optimal CO_2 levels and occupant comfort. [20] showed a significant deterioration in health performance corresponding to a CO_2 level of more than 1000 ppm in their study. According to ASHRAE Standard 62–2001, Section 6.1.3, comfort criteria are likely to be met if the ventilation rate did not exceed 1,000 ppm of CO_2 level.

ASHRAE 62, 2004 edition, revised Section 6.1.3 to include a 700-ppm difference in indoor and outdoor CO_2 concentrations as an acceptable level of human bio-effluents based on a specific ventilation rate (15 cfm/person) and outdoor CO_2 concentration of 300 ppm. In this regard, CO_2 sensor plays a vital role and is essential for DCV. It measures the CO_2 concentration in the room and outputs the command variable. DCV based on CO_2 concentrations in a space could maintain the air quality and improve the energy efficiency of the HVAC system [21]. The traditional methods for controlling airflow using a damper at the fan outlet reduced total energy consumption, but they also reduced fan static pressure and waste fan power [22]. In view of this matter, ventilation is a cornerstone of healthy and energy-efficient building design, balancing the need for indoor air quality (IAQ) with energy conservation. In office environments, particularly those situated in tropical climates, this balance is crucial yet challenging due to the high humidity and temperature conditions inherent to these regions. While DCV systems have been recognized for their potential to optimize energy use and maintain IAQ by adjusting ventilation rates based on occupancy, the bulk of research on DCV has been conducted in temperate climates. These studies underscore the system's capability to significantly reduce energy consumption while ensuring indoor air remains within healthful parameters.

However, a comprehensive review of the existing literature reveals a conspicuous gap: there is a lack of research focusing specifically on the application and effectiveness of DCV systems in tropical office spaces. This oversight is notable, as the unique climatic conditions of tropical regions, characterized by their consistently high temperatures and humidity levels can influence the performance and efficiency of DCV systems in ways that differ markedly from temperate settings. The absence of detailed studies in this area leaves a critical void in our understanding of how DCV systems can be optimized for tropical climates, thus limiting the applicability of current knowledge to a significant portion of the global context.

3. Methods

This research adopts a pioneering simulation-based methodology to evaluate the impact of Demand Control Ventilation (DCV) on the indoor air quality (IAQ) and energy efficiency within a tropical office setting. Utilizing the advanced Carrier's Hourly Analysis Program (HAP) software, we model and simulate the nuanced dynamics of HVAC systems specific to tropical climates, characterized by high humidity and temperature fluctuations.

3.1 System Modeling and Validation

The first step involved modelling the existing HVAC configuration of our tropical office case study building in HAP software. This phase is crucial for creating an accurate and comprehensive data of the ventilation and air conditioning systems, ensuring the simulation's reliability. By incorporating real-world data from the building into our model, we validate the simulation against actual performance metrics, bridging the gap between theoretical analysis and practical application. This validation ensures our findings are grounded in reality, enhancing the credibility of our simulation outcomes.

3.2 DCV Integration and Optimization

Subsequently, we explore the integration of DCV into the existing system, focusing on optimizing the design for maximum IAQ improvement and energy efficiency. This step involves a detailed analysis under various operating conditions, simulating the office's unique tropical environment. By adhering to international standards such as ANSI/ASHRAE 62.1, 62.2, ASHRAE Standard 55, and Malaysian Standard MS:1525, we ensure our DCV design not only meets global benchmarks but is also tailored to address the specific challenges posed by the tropical climate.

3.3 Impact Analysis

Leveraging the simulation model, we assess a spectrum of IAQ parameters, energy consumption patterns, and greenhouse gas emissions under different scenarios. This comprehensive analysis offers insights into the DCV system's efficacy in enhancing energy efficiency and improving IAQ in tropical office environments. The methodological framework, supported by rigorous simulation and validation, provides a robust basis for evaluating HVAC performance and the transformative impact of DCV in tropical settings.

3.4 Tropical Climate-Specific Case Study

An office space of a local university in Kota Samarahan, Sarawak was chosen as our case study offers a unique lens through which to examine DCV's effectiveness in a tropical climate. This contextually rich investigation not only highlights the DCV system's adaptability but also underscores its potential to significantly reduce energy consumption and maintain optimal IAQ in tropical office environments. This single-storey office space of brick wall building is incorporated with 28.6 m^2 of glass walls and doors, as shown in Fig. 3.1.

In this office space, the estimated number of occupants is 25, and the total air-conditioned floor area measures 410 m2. The electrical equipment load is estimated to be 1652 Watts, primarily attributed to the lighting equipment. The HVAC system employed in this case study is of the direct expansion fan coil type. It operates with a constant fresh air volume but allows for variable fresh air temperature control. This configuration enables flexibility in maintaining optimal indoor conditions while considering energy efficiency.

For this case study, the initial setup of the HVAC system in the office space involved a constant outdoor fresh air inlet, which did not consider the occupancy levels. This approach resulted in good indoor air quality (IAQ) but led to higher energy costs for cooling, heating, and dehumidification, as highlighted by reference [14]. To address this issue, a common conservation action is the installation of a Demand Control Ventilation (DCV) system, which allows for the control of fresh air intake based on demand rather than a fixed volume.

In this particular case study, the DCV system implemented utilizes CO_2-based control. CO_2 sensors are integrated into the Air Handling Unit (AHU) system to continuously monitor indoor CO_2 levels. Real-time feedback from these sensors enables the DCV system to regulate the amount of fresh air brought in for ventilation.

CO_2 sensors have proven to be highly effective in managing ventilation and are widely accepted as a legitimate solution in accordance with building standards such as ASHRAE Standards. To analyse the IAQ and energy performance in this case study, the Carrier Hourly Analysis Program (HAP) was employed. The selected parameters for assessment included electricity consumption, carbon dioxide levels, average relative humidity, and average temperature in the office space.

All simulation input data were based on the original design conditions and actual equipment present in the office space. The HVAC set point, estimated occupancy, air-conditioned floor area, and estimated electrical equipment load were among the inputs used in the Carrier HAP software to generate monthly data for electricity consumption and indoor air quality. It should be noted that the simulation results are specific to the IAQ and energy efficiency assessment of the office space under study. The selected parameters may differ depending on the specific activities taking place within a building.

4. Results and Discussion

4.1 Evaluation of the IAQ and energy consumption in an office space

Table 4.1 shows the simulation output data of the IAQ and energy consumption for the office space case study before the installation of the DCV, using the Carrier HAP.

Table 4.1
Monthly office space case study data of the energy consumption and IAQ before the installation of DCV

Month	EC (kWh)	IAQ – AT (°C)	IAQ - RH (%)	IAQ - CO_2 (ppm)
Jan-19	19349	24.8	72.0	514
Feb-19	18949	24.9	71.2	514
Mar-19	20565	24.9	70.7	512
Apr-19	23394	24.9	70.9	510
May-19	23787	24.8	71.5	510
Jun-19	21772	24.9	71.1	511
July-19	23306	24.9	70.1	510
Aug-19	20863	24.9	70.1	512
Sep-19	21104	24.9	70.3	512
Oct-19	21860	24.9	70.8	511
Nov-19	19012	24.8	72.0	514
Dec-19	20585	24.8	72.3	512

The results indicate that energy consumption values vary each month, exhibiting periodic increases with notable spikes, particularly in April, May, and July. These elevated peaks in electricity consumption during these months can be attributed to the heightened operation of the HVAC system, aimed at maintaining the desired indoor air temperature, given the warmer ambient conditions prevalent during this period. Additionally, our observations reveal an inverse relationship between relative humidity and electricity consumption, as humidity decreases in tandem with the increase in electricity usage from March to April. Further investigations suggest that both human occupancy and electrical equipment contribute to the release of CO_2 gas within the office space. Consequently, the HVAC system plays a crucial role in mitigating CO_2 concentrations by introducing fresh air to dilute the indoor air.

It is worth noting that spaces that offer superior thermal comfort tend to exhibit lower CO_2 concentrations. However, adhering to the ASHRAE Standard 62.1–2013, which mandates that CO_2 levels in an office space should remain below 1,000 ppm, necessitates careful management of fresh air intake to reduce energy consumption for the cooling process. This relationship underscores the correlation between indoor air quality (IAQ) in terms of CO_2 levels and electricity consumption.

In this specific case study, the HVAC system employs a constant air volume strategy without any control mechanism based on CO_2 concentration levels within the office space. Consequently, an excess of fresh air intake occurs, resulting in an unnecessary increase in electricity consumption due to the additional cooling load. Therefore, it becomes imperative to enhance the ventilation rate to bolster the energy efficiency of the office space. To achieve this objective, the implementation of Demand-Controlled Ventilation (DCV) will be explored in the subsequent sections as a tool to optimize ventilation rates and ultimately enhance energy efficiency.

4.2 Utilisation of DCV for Energy Efficiency and IAQ Improvement

The results in Table 4.1 show that the IAQ-CO_2 level has a significant impact on energy consumption. One of the usual conservation actions taken is by installing the HVAC system with a DCV to control the fresh air intake in order to ensure the fresh air intake is based on demand, and not a constant volume. The DCV was selected in the Carrier HAP program. Table 4.2 shows the simulation result of the energy consumption and IAQ, whereas Fig. 4.1 shows the energy consumption graph before and after DCV installation.

Table 4.2
Monthly office space case study data of the energy consumption and IAQ after the installation of DCV

Month	EC (kWh)	IAQ-AT (°C)	IAQ-RH (%)	IAQ-CO_2 (ppm)
Jan-20	12442	24.80	71.63	714
Feb-20	11425	24.85	71.00	714
Mar-20	12500	24.87	70.25	714
Apr-20	13356	24.86	71.00	714
May-20	13615	24.85	71.19	714
Jun-20	12738	24.88	70.88	714
Jul-20	13853	24.85	70.13	714
Aug-20	12563	24.92	69.88	714
Sep-20	12796	24.90	70.06	714
Oct-20	13300	24.90	70.50	714
Nov-20	11772	24.83	71.38	714
Dec-20	12848	24.78	72.06	714

The results indicate that following the installation of Demand-Controlled Ventilation (DCV), energy consumption exhibited a noteworthy decrease, averaging 38.9%, as illustrated in Fig. 4.1. This substantial improvement can be attributed to the effective control of fresh air intake, resulting in CO_2 levels being maintained below 800 ppm. Furthermore, indoor air temperature remained within the range of 24.5–28°C, and relative humidity was kept below 60% RH. These findings underscore the HVAC system's ability to uphold a commendable Indoor Air Quality (IAQ) while optimizing fresh air intake, thereby alleviating the workload on the HVAC compressor and concurrently reducing electricity consumption. A more detailed analysis of the operational activities during the month of February revealed a reduction in energy consumption, which can be attributed to the lower number of working days compared to other months. With fewer working days, the overall operational load decreased, consequently resulting in a reduction in the intensity of the selected parameters.

5. Conclusions

This study set out to assess the substantial impacts of integrating Demand-Controlled Ventilation (DCV) within tropical office settings, emphasizing its pivotal role in simultaneously enhancing Indoor Air Quality (IAQ) and augmenting energy efficiency. By ingeniously regulating ventilation rates to align with real-time occupancy, the study illuminates how DCV systems ingeniously maintain optimal IAQ parameters including CO_2 levels below 800 ppm, indoor air temperatures within a comfortable range of 24.5–28°C, and relative humidity under 60%, while precipitating a remarkable average reduction in HVAC energy consumption by 38.9%. The primary driver of this energy savings was the ventilation rate, as evidenced by a substantial decrease in electrical consumption when DCV-controlled ventilation was introduced. The implications of these findings are profound, advocating for the wide-scale adoption of DCV in both retrofit and conservation initiatives across tropical regions, thereby offering a sustainable blueprint for future office design that prioritizes environmental responsibility without compromising on occupant comfort or operational efficiency. This work not only underscores the viability of DCV as a transformative solution for contemporary office environments but also contributes a significant scholarly discourse on the optimization of ventilation systems for ecological and economic benefits in the face of global climate challenges.

Abbreviations

AHU Air Handling Unit

DCV Demand Control Ventilation

IAQ Indoor Air Quality

HVAC Heating, Ventilation, and Air Conditioning

HAP Hourly Analysis Program

DOSH Department of Occupational Safety and Health

CAV Constant Air Volume

CO_2 Carbon Dioxide

ppm parts per million

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers

RH Relative Humidity

EC Energy Consumption

AT Average Temperature

kWh Kilowatt Hours

°C Degree Celsius

Declarations

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Authors' contributions

MAM and AC contributed to the design of DCV and analysed the data simulations. GI aided in interpreting the results and worked on the manuscript. ASMP collected data from the existing building and carried out the model simulations, designed the figures, and wrote the manuscript in consultation with MAM. The author(s) read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

Data available on request due to privacy restrictions.

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Figures

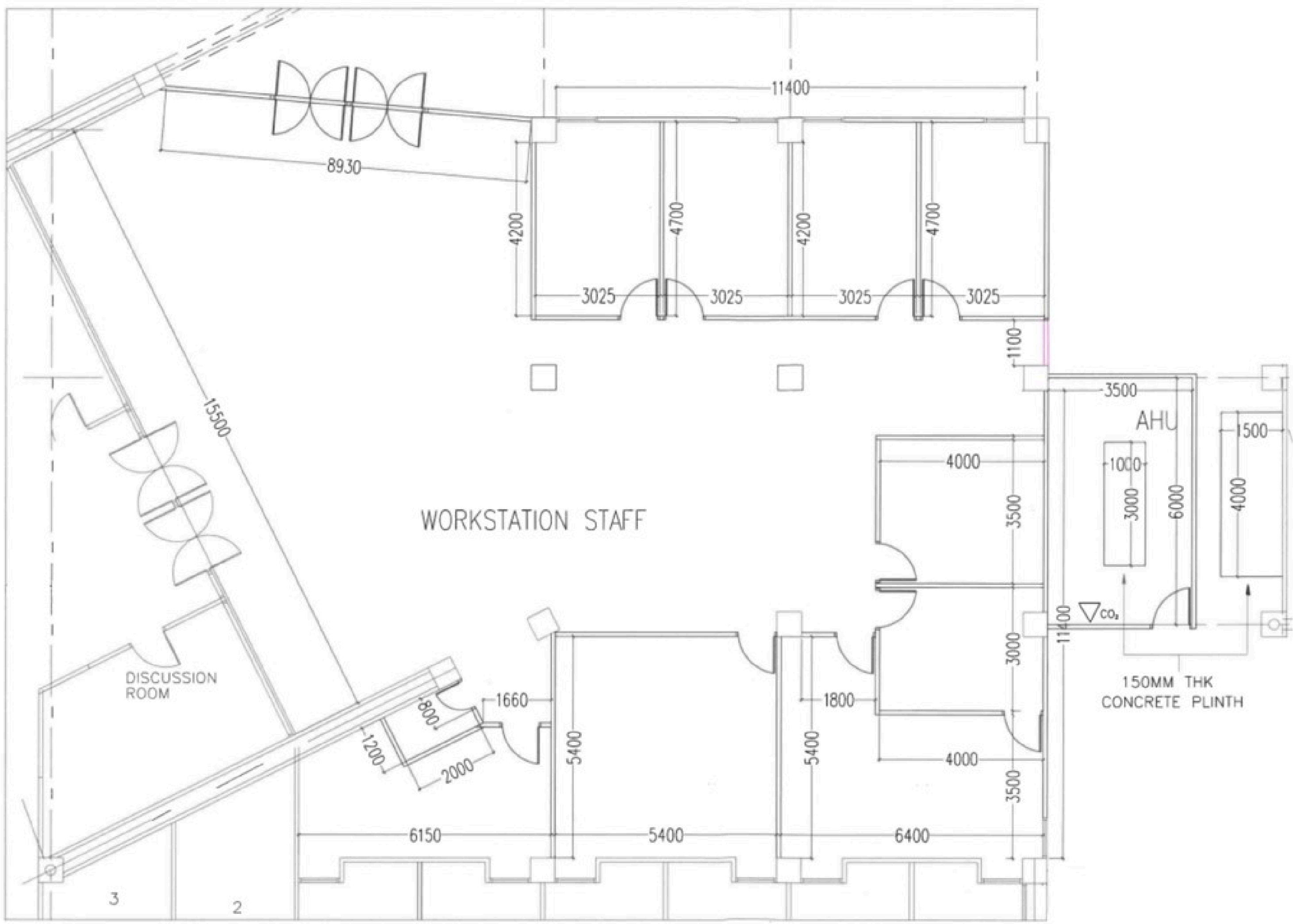

Figure 1

Figure 3.1 Layout Plan of the Office Space Case Study

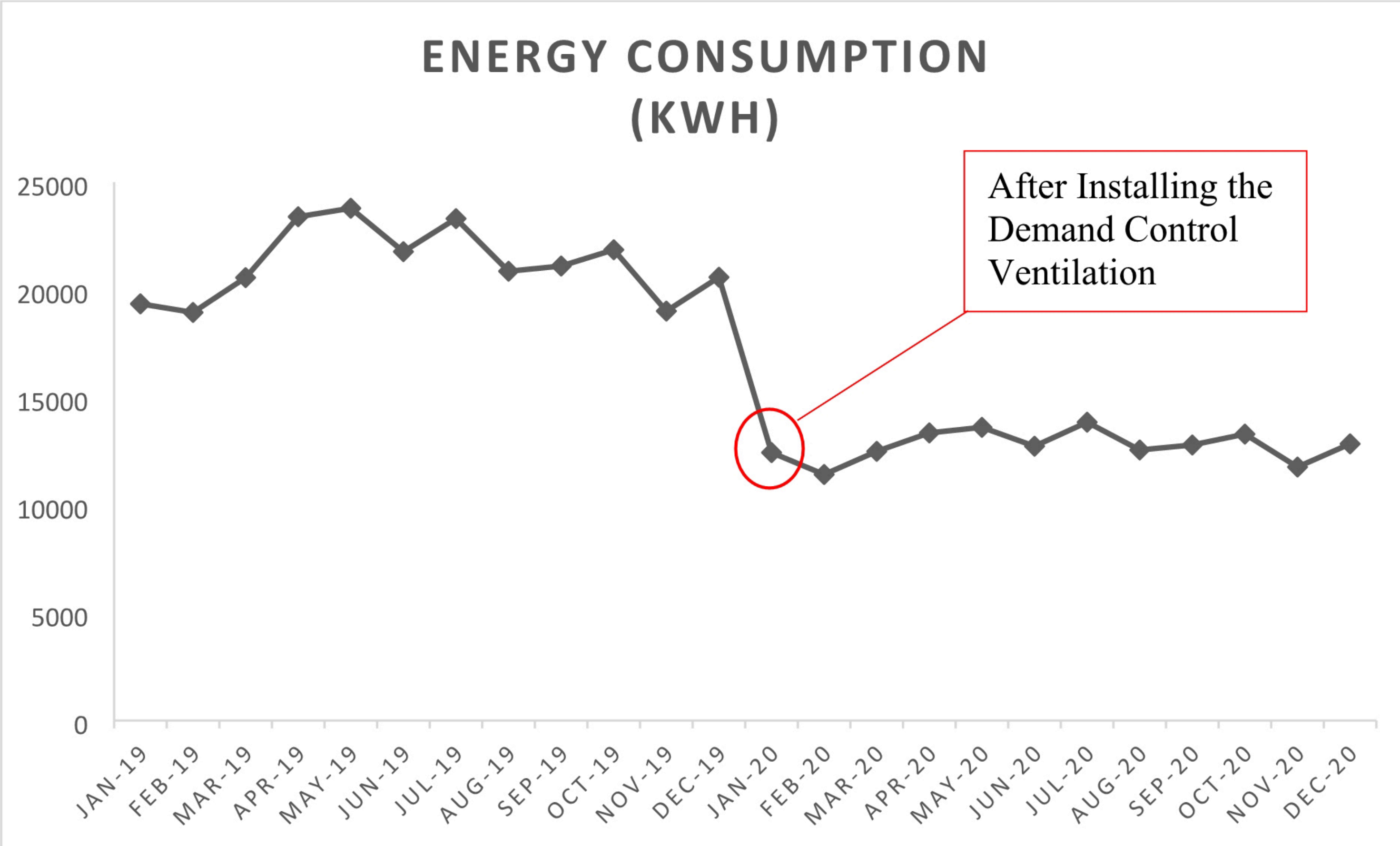

Figure 2

Figure 4.1 Office space energy consumption trend after the installation of DCV