POTENTIAL OF USING VARIABLE AIR VOLUME SYSTEMS AGAINST CONSTANT AIR VOLUME SYSTEMS FOR MEDIUM SIZE OFFICE BUILDINGS

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DECLARATION

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(Prof. R. A. Attalage)

ABSTRACT

It is a popular fact among HVAC designers that variable air volume (VAV) systems are energy efficient than more common constant air volume systems. Despite that information, when comes to the selection stage of the most suitable air side system for the project, the designers falter to suggest a VAV system to the client with the higher installation cost yielded by the VAV system in his mind. It is nice if he has the luxury finding the pay back of the VAV system after modelling the building and doing a simulation. But, in reality it is a time consuming and tedious task in a busy schedule. It will be immensely helpful if the HVAC designer can decide whether to go for VAV or Constant Air volume (CAV) by just a careful study on some straight forward facts of the building.

Therefore, this research is focused on developing a guideline in to decide whether to go for VAV or CAV for a midrise office building. It was done with the help of TRACE 700 energy simulation software. Few sample buildings are modelled with TRACE 700 in few orientations and a comparison was done taking the CAV system as base design and VAV as alternative. Life cycle analysis is done using the present tariff structures of Ceylon Electricity Board.

The results of this research are based on two defined parameters as solar gain factor (SGF) and occupancy diversity factor (ODF). SGF is defined as ratio of solar gain to total cooling load of the building which can be obtained by basic cooling load calculation. ODF is a measure of average occupancy variation of the building. Lower the ODF value means higher the occupancy variation. The building category underwent to this research is mid-rise office buildings (i.e. height between 18m – 30m) and the ODF value for those buildings are between 64% and 80%. For a highly varied occupancy schedule, ODF is 64% and for a uniform occupancy schedule, it is 80%. For those ODF value range, the VAV benefited SGF value range is identified as 11.9-13.4 for a payback period of five years. That means, for a mid-rise office building, VAV system is benefitted for a SGF value range of 11.9 – 13.4. If the SGF is lower than 11.9 in a mid-rise office building, VAV systems are not economical when considered for a payback period of five years or less. For any SGF value in above range, the life cycle payback period can be determined using above linear relationship between SGF and life cycle payback period for a selected ODF value between 64% and 80%. For any exception with ODF values higher than 80%, a complete building simulation should be carried out to determine the required SGF value for that building. Otherwise, the investment for VAV will not be paid back within reasonable time (within five years as considered in this study). On the

other hand, for a building with lower ODF than 64%, the investment on VAV is worth even in a SGF value lower than 11.9. Further studies should be carried out for the situations out of those ranges.

The significance of some non-quantitative benefits of VAV systems is also highlighted.

ACKNOWLEDGEMENT

It is a pleasure to acknowledge Prof. Rahula Attalage who guided me towards the optimum objectives of this research.

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Also I would like to thank Central Engineering Consultancy Bureau for providing me essential data, facilities and sponsorship to make this successful.

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NOMENCLATUTE

VAV	Variable Air Volume
CAV	Constant Air Volume
VSD	Variable Speed Drive
AHU	Air Handling Unit
CEB	Ceylon Electricity Board
CECB	Central Engineering Consultancy Bureau
G.P. - 2 CEB	General Purpose Tariff for each individual point ofsupply delivered and metered at 400/230 Volts nominaland where the contract demand exceeds 42 kVA
ASHRAE	American society of Heating, Refrigeration and Air Conditioning Engineers
TRACE 700	Trane Air conditioning Economics Software developedby Trane Air Conditioning Company, United States ofAmerica
TR	Tons of Refrigeration

LIST OF APPENDICIES

1.0 INTRODUCTION

1.1 Background

In few decades ago, buildings were designed like a part of the environment itself. When the occupants come into the building, they felt very little artificial in the building. Because, most of the lighting was natural lighting and ventilation was natural ventilation. In one hand, they had the luxury of using natural lighting and ventilation because the environment was not as polluted as now. On the other hand, lack of modern technology made them to do that. These buildings were sustainable in energy wise, but there were some concerns about security, secrecy etc.

At present, although the using of natural light is still a major concern, building designers are not very convenient with using natural ventilation for a building amidst a congested city due to hundreds of practical problems. In that sense, air conditioning is becoming a necessity more than a luxury.

Approximately 60% of total building electricity consumption goes towards air conditioning in an air conditioned building. [Detlef Westphalen, Scott Koszalinski. Energy Consumption Characteristics of Commercial Building HVAC Systems: Volume II: Thermal Distribution, Auxiliary Equipment, and Ventilation. Cambridge: Arthur D. Little, Inc., 1999]In this situation it is necessary to find possible strategies which will reduce air conditioning power consumption. There are thousands of researches being done in search of ways to reduce that amount. Improvements on chillers, cooling towers, pumps and optimized sequences of above equipment are the major concerns on those researches. In recent times, there is an escalated motivation on air side improvements also. Air side economizers and Variable air volume are the mostly focused areas in air side improvements.

Various air supply technologies have been developed for HVAC systems. The spaces that have no complex load fluctuations can be considered as a single zone and these can be easily catered with Constant Air Volume systems. But, in handling different fluctuating loads with a single AHU, systems like dual duct system, multi zone system and Variable Air Volume system are developed. But, multi zone systems and dual duct systems are not recommended for most of the situations because they waste a lot of energy. In general, Constant air volume (CAV) and variable air volume (VAV) are the two common methods of designing air side of HVAC systems. CAV is simpler and less expensive in capital cost and VAV is in opposite side considering above two factors. But when talking about energy efficiency and precise controllability, VAV is substantially better than the CAV system.

Selecting a suitable air side option for a HVAC system is a compromise between capital cost and operating cost. For a large system, the operating cost component becomes more critical and hence investing more on capital cost in order to reduce operating cost is more explainable. But, when the system becomes smaller, the operating cost component becomes less critical and more investment on capital cost can be less economical. There is no clear quantitative boundary between these two options.

When considering the requirements of green building certifications, energy efficient systems should be preferred against less expensive high energy consuming systems. It is a responsibility of engineers to motivate their clients to think about minimizing energy usage. In this regard, VAV technology is an option with high potential.

On the other hand the interest on VAV is not merely due to energy factor, but it is a system that ensures more occupant satisfaction as a multi zone system. Selecting a VAV system is an investment which is good in energy conservation as well as functionality of the system but has a vague pay back. Therefore, more literature should be provided on these technologies for the designers.

1.2 Objective

The main objective of this research is to check the usability of a VAV system for a midrise office building in various load fluctuations and orientations. Further, it can be extended to a guideline in selecting a suitable air system for a HVAC system in various magnitudes.
The objectives of the research can be listed as follows.

- Checking the usability of a VAV system for a midrise office building in various conditions.
- Developing a guideline to select the most suitable air side system for a mid-rise office building.

1.3 Approach and methodology

- Modelling two medium rise office buildings (medium rise building is a building having height between 18m and 30m [Institute for Construction Training and Development. “Fire Regulations”. Sri Lanka. ICTAD/DEV/14. Dec 2006]) using a CAV as the base design and VAV as the alternative.
- Calculating initial costs, maintenance costs, operating costs and energy consumption for the two options.
- Using those facts, comparing the life cycle cost and pay back periods of alternative option over base design.
- Repeating the above steps for various orientations of the building.
- Carrying out a case study on the results and developing the objectives.

1.4 Contribution

The contribution of this research is developing some benchmarks / norms to aid designers who consider VAV systems for medium rise office buildings. With the help of the outcomes of this research, a designer can carry out a pre-assessment whether he can consider a VAV system for his building.

2.0 LITERATURE REVIEW

2.1 Overview of VAV systems

2.1.1 Background

The main purpose of any HVAC system is to provide thermal comfort. The main parameters effect on thermal comfort are temperature and humidity. If a sample of building occupants are considered, each one get thermally satisfied at different temperature and humidity combinations. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) have established a range of room conditions that are acceptable for most building occupants. This is called comfort zone. Figure 1 shows the comfort zone for majority of occupants as defined in ASHRAE Standard 55. The comfort zone can be different for level of clothing, nature of work doing etc.

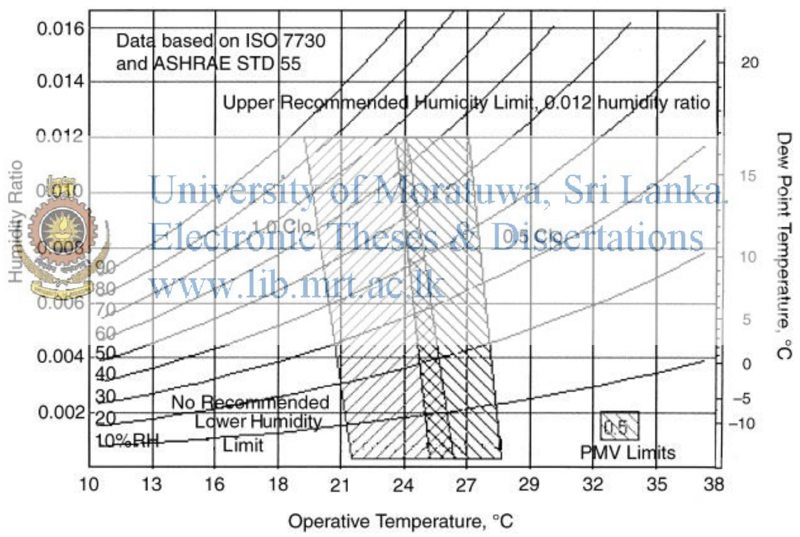

Figure 1: Comfort zone
[ASHRAE. "Thermal Environmental Conditions for Human Occupancy" U.S.A. 2004]

Despite the space is thermally comfort, there is another critical aspect that affects the occupants. That is indoor air quality (IAQ). The most important parameter of IAQ is CO_2 percentage in the breathing zone. As an amount of people occupy a space, the CO_2 level can go up with time. Therefore, **Ventilation (outside air)** must be provided to every occupied building. Building codes specify the amount of ventilation air that must be introduced by the HVAC system. ASHRAE 62.1 has specified the amount of outdoor air that should be provided for various types of spaces.

2.1.2 Why VAV

As a summery, an HVAC system maintain the spaces with an acceptable combination of humidity and temperature within the comfort zone while providing a sufficient amount of outside air for ventilation. The set of equipment that handles the supply and ventilation air of the HVAC system is air side system. The effectiveness control of the air side system depends upon two factors:

- The quantity of air being supplied
- The temperature of the supply air

In capacity control of a HVAC system, these two factors are combined in different combinations depending upon the type and design of the particular HVAC system. The combinations are:

- Constant Volume-Variable Temperature
- Variable Volume-Constant Temperature
- Variable Volume-Variable Temperature

As a norm, constant volume variable temperature system is less expensive in installation. Also functions well for a single space, but problem arise when catering multiple spaces. Figure 2 illustrates the normal occupant feedback in such a case.

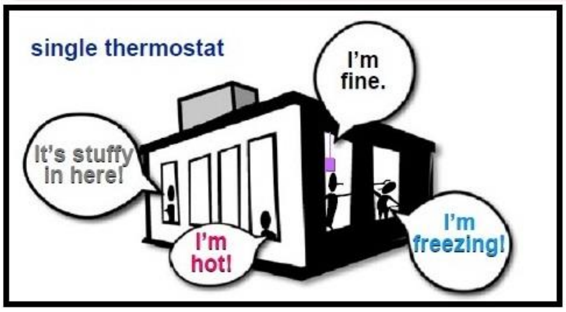

Figure 2: Multiple spaces with single thermostat
[Trane Company. “Air Conditioning clinics – *VAV systems,”* presented at Trane technical session, Colombo, Sri Lanka, 2014.]

If a building has many spaces with diverse cooling needs, each must be served by its own system.To serve multi spaces with single AHU, the cool primary air must be either reheated or mixed with warm air to produce the supply temperatures needed to balance the various space cooling loads.This is done in terminal reheat system and dual duct system respectively.

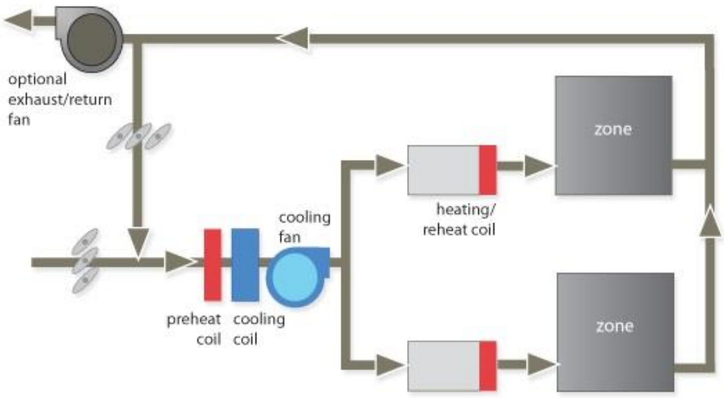

Figure 3: Terminal reheat system
[Trane Company. "Air Conditioning clinics – *VAV systems,"* presented at Trane technical session, Colombo, Sri Lanka, 2014.]

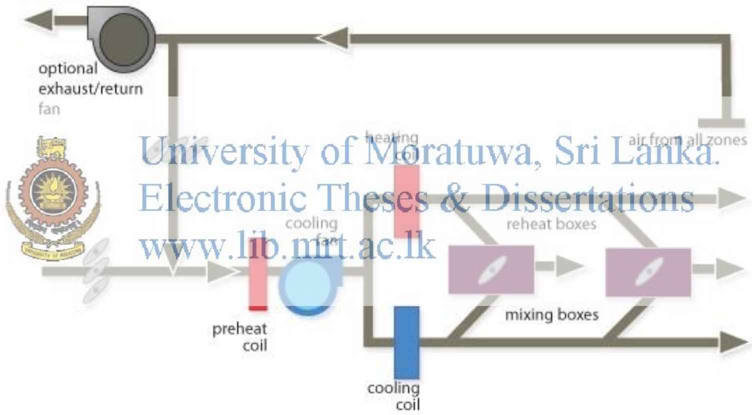

Figure 4: Dual duct system
[Trane Company. "Air Conditioning clinics – *VAV systems,"* presented at Trane technical session, Colombo, Sri Lanka, 2014.]

Above two systems can satisfy occupants in individual spaces. But both these systems have their detriments in energy aspect. The table below summarizes the pluses and minuses of above two systems and VAV system.

Constant-volume, single zone	**Constant-volume, terminal reheat**	**VAV**
Constant fan energy	Constant fan energy	Fan energy savings
Refrigeration energy	Nearly constant refrigeration	Refrigeration energy

savings Delivers comfort to only one thermal zone	energy Delivers comfort to many spaces inefficiently Reheat energy increases at part load	savings Delivers comfort to many spaces efficiently

2.1.3 Theoretical background of VAVs

Fans are selected for air handling units to deliver the maximum airflow required to meet peak load conditions of the space. However, the space reaches its peak load conditions only for short periods of time and the capacity of air handling units is controlled to match requirements by varying the supply air temperature or the amount of air supplied.

In constant air volume (CAV) systems, the capacity is controlled by varying the supply air temperature. In such systems, the fan is operated at a fixed speed to give a constant volume of air. In part load conditions, the supply air temperature is increased keeping the quantity of air unchanged. The increase of supply air temperature may keep the room temperature at design level, but increase the relative humidity in the space. On the other hand, running the fan constantly irrespective of the load is wastage.

Variable air volume systems can overcome this energy wastage by changing the air quantity against building load. There are few mechanisms used in VAV. Those are, discharge dampers, inlet guide vanes, or variable speed drives (VSD). Among those, the most popular is VSD type as it has more energy savings over other 2. Figure 2.1 illustrates a comparison of energy consumption of above 3 types of VAVs.

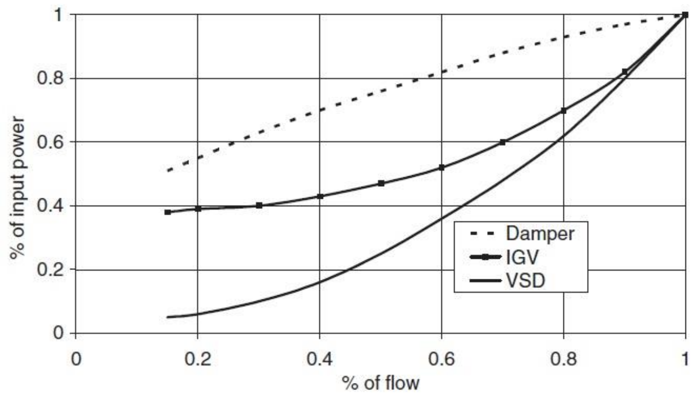

Figure 5; Fan energy consumption in different VAV systems.

[Dr.Lal Jayamaha, *Energy Efficient Building systems* – Green Strategies for Operation and Maintenance, Singapore: McGrow-Hill Companies, 2006]

In VSD type VAVs, in part load conditions, the VSD adjusts the fan curve to get the optimum operating point of the fan. According to the affinity laws, the fan power consumption (P) is proportional to the cube of flow rate (Q).

$P \alpha Q^3$ ——— (1)

Therefore, theoretically, at 50 percent flow condition, the fan power consumption is 12.5% (0.53 = 0.125) of the maximum power consumption. This shows that it is possible to reduce the power consumption significantly at part load conditions by using a variable speed drive.

The figure 6 illustrates how the shifting of fan curve meets the optimum operating point keeping the system curve constant.

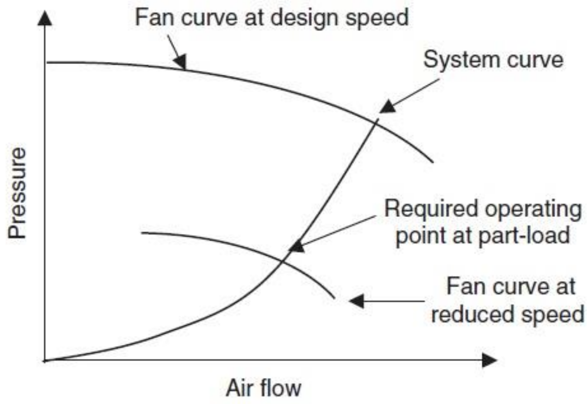

Figure 6: Reducing air flow at part load by reducing fan speed

[Dr.LalJayamaha, *Energy Efficient Building systems* – Green Strategies for Operation and Maintenance, Singapore: McGrow-Hill Companies, 2006]

The controlling function of the VAV starts with the room temperature sensor. When part load conditions arrived, the VAV box adjusts its position which increases the static pressure of the air distribution system. Then, the pressure transducer sends the signal to VSD to adjust the fan speed. Adjusting the fan speed is not a strait forward action. It has a sequence of trial and error functions with continuous feedbacks from pressure transducer and temperature sensor. The figure 7 illustrates the typical arrangement of a VAV system.

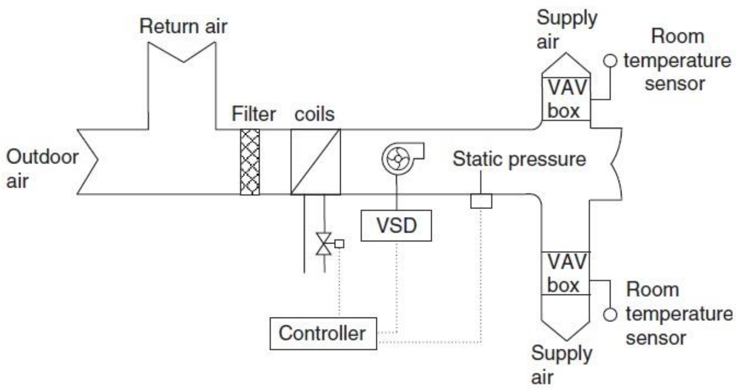

Figure 7: Typical arrangement of a VAV system

[Dr.LalJayamaha, *Energy Efficient Building systems* – Green Strategies for Operation and Maintenance, Singapore: McGrow-Hill Companies, 2006]

2.1.4 Types of VAVs

There are many different types of VAV units:

- Single Duct / cooling only, or cooling with reheat

- Dual Duct terminal
- Induction VAV terminal
- Parallel Flow Fan Powered VAV terminal
- Series Flow Fan Powered VAV terminal
- By pass VAV

VAV terminals are also classified as pressure independent and pressure dependant.

In pressure-dependent VAV control scheme, the damper position is adjusted by the space temperature sensor. The actual air flow delivered to the space is a function of this position and depends on the duct system static pressure at the inlet of the terminal unit. Although the space temperature sensor will continually correct the position of the modulating device, the response time can cause unacceptable temperature variations within the space.

A pressure-independent VAV control scheme directly controls the actual volume of primary air that flows to the space through an airflow-measuring device on the terminal unit. The position of the modulation device is not directly controlled by temperature sensor and is basically a by-product of regulating the air flow through the unit. Because the airflow delivered to the space is directly controlled, it is independent of inlet static pressure.

Pressure-independent control is the most popular VAV terminal unit because it increases the stability of airflow control, and allows minimum and maximum airflow settings to become actual air flows rather than physical positions of the modulation device.

2.1.5 Facts related with VAV in various standards

ASHRAE Standard 90.1-2007 (I-P Edition)

This is the energy standard for buildings except low rise buildings. It has specified their requirements on VAV systems under 03 areas.

Part Load Fan Power Limitation – It is recommended for VAV fans with motors larger than 10 hp to be either driven by a mechanical or electrical variable speed drive or to be a vane-axial fan with variable-pitch blades. If the motor is not under both above categories, it should have other controls and devices that will result in fan motor demand of no more than 30% of design wattage at 50% of design air volume when static pressure set point equals one-third of the total design static pressure, based on *manufacturers'* certified fan data.

Static pressure sensor location –The static pressure sensor should be located in the supply duct system such that controller set point equal or less than one-third the total design fan static pressure, except for systems with zone reset control. Otherwise, multiple sensors should be used.

ASHRAE Standard 62.1 – 2007

This standard is related with indoor air quality. It specifies that in a VAV system, if the outdoor air damper is fixed, its position should be designed such that to provide the minimum outdoor air volume for the space at any load condition.

Code of practice for Energy Efficient buildings in Sri Lanka – 2008

This code was developed by sustainable energy authority of Sri Lanka. It has specified requirements on minimum air volume per kW of total input power for the motors to provide the combined fan system at design conditions. For CAV, it is 590 l/s and for VAV, it is 420 l/s.

2.1.6 Drawbacks and areas to be improved

Maintaining indoor air quality in part load conditions

Normally, the VAV terminal is controlled by the zone load. But the zone can vary with the external loads like solar gain as well as internal loads like occupancy. The fresh air requirement depends on occupancy and area according to ASHRAE 62.1. In a situation where the total load is decreased due to a decrease in solar gain, the fresh air requirement remains unchanged. But, if the fresh air louver is centralized, the fresh air amount decreases proportionate to the total load. That can make the zone lack of ventilation.

This is the most identified problem arise in VAV systems. There are few solutions for that.

- Maintaining a minimum air flow and using a terminal reheat
- Supply air temperature reset using occupancy sensors
- Demand controlled ventilation using CO_2 sensors

2.2 Studies and researches on VAV

There are many studies and researches done to optimize the usage of VAV systems over other air side strategies. Following chapter illustrates some overviews of researches done and few studies on some VAV systems installed in Sri Lanka.

2.2.1 Research 01- A research completed by ASHRAE - research project (RP-1515)

This study has been performed in various locations of Northern California. They have collected information such as occupant satisfaction, equipment operation, and energy use of a base design which was a single-duct VAV terminal with hot water reheat and DDC.

In base design, the flow rates on interior zones were designed at 1 cfm/ft^2 (0.5 L/s · m^2) with higher rates for perimeter zones, depending on orientation. Minimum flow rate of VAV was set at 30% of maximum. Plaque type diffusers were installed to deliver air to the space.

The hot water for reheating purpose was supplied by a natural gas boiler. In monitoring natural gas use for this boiler, it has been observed that the boiler was being operated throughout the year by the system as the interior zones were yielding reheat every afternoon. Meanwhile, occupants were complaining that it was too cool in many interior locations. They have tried by reducing minimum air flow rate down to 10% of minimum and by trial and error process it was compromised at 20% which has increased occupant satisfaction considerably. Interestingly, no complaints have received about low motion of air at this 10% of design load which is normally a concern with VAV systems. The locations received the minimum air flow requirement of 0.1 cfm/ft^2 have reached to 100% of outdoor air according to the ventilation codes of California.

The studies at other locations also have received similar observations by which they have concluded the following.

- VAV systems at very low flows can provide acceptable environments, if the temperature is controlled.
- Designing for 1 cfm/ft^2 (0.5 L/s·m^2) is likely far too much air; minimums need to be set below 0.3 cfm/ft^2 (0.1 L/s·m^2).
- The ventilation load is the most important load in the interior zone.
- VAV minimums set too high will sub cool the space, causing occupants to complain, or worse, run space heaters. VAV terminals may go into reheat.

2.2.2 Research 02 – conducted by Mari-Liis Maripuu and Lennart Jagmar

[Mari-Liis Maripuu, Lennart Jagmar. "Energy savings by changing constant air volume systems to variable air volume systems in existing office buildings. – Experience from a plant reconstruction based on a new supply air terminal device concept." M Eng Thesis, Building Services Engineering, Chalmers University of Technology, Gothenburg, Sweden.]

Approach

They have introduced a new type of VAV supply air diffuser, which allows supplying the air into room with low temperature (around +15°C) without causing any thermal comfort problems. Schematic picture of this device is given below.

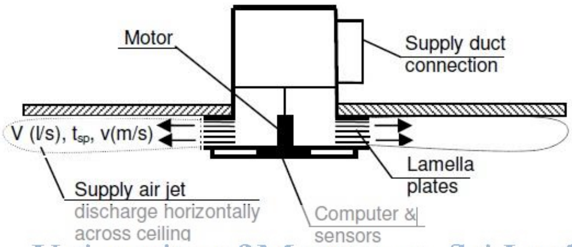

Figure 8: VAV supply air diffuser (from above reference)

This diffuser has been installed in a university building in Chalmers in Gothenburg replacing all ordinary supply air devices. The supply and exhaust air fans have been converted to VFD in order to maintain a specific static pressure in the main duct near the air handling unit.

Results

Table below gives the energy consumption comparison before and after the modification.

Table 1: Energy consumption comparison before and after the modification

System parameter	**Before rebuilding** **CAV system**	**After rebuilding** **VAV system**
Heat recovery -temperature efficiency	75%	78%
Maximum air flow rate	6,5 m3/s	5,6 m^3/s
Operation time	3500 h/year	3500 h/year
Supply air temperature	18°C	15°C

Exhaust air temperature	21°C	21°C
Outdoor climate	Göteborg	Göteborg
Specific fan power- SFP	2,5 kW/m^3/s	av1,2 kW/m^3/s
Necessary annual heat energy	12,5 MWhheat	0 MWhheat
Necessary annual electric energy	57 MWhel	21 MWhel
Necessary annual cooling energy	44,0 MWh cooling	56,7 MWh cooling

Based on above results, they have developed following conclusions.

- Although a lot of researches have been done to prove the potential of VAV system as one of the most energy efficient ways for building air-handling system, there is still a problem with the high cost of this system. Therefore, the possible effort of it should be maximized.
- All different parts of a VAV system have a significant role for the total functioning of it. Also costs of the different parts vary a lot. Installing variable frequency inverters for the fan speed control for both supply and exhaust air fans is one of the lease expenses of the total VAV system comparing with building air distribution parts. But both aspects play significant roles in the total functioning of the whole ventilation system. Therefore they must fulfil certain requirements. Providing good indoor climate with less use of energy is part of it.
- VAV system with low supply air temperatures gives bigger energy savings.
- Lower supply air temperatures also require diffusers that will maintain required indoor climate.

2.2.3 Research 03-

[Mehmet Azmi Aktacir, Orhan Bu¨yu¨kalaca, TuncayYılmaz. “Life-cycle cost analysis for constant-air-volume and variable-air-volume air-conditioning systems.” Post graduate research, Department of Mechanical Engineering, University of C¸ ukurova, Turkey, 2004.]

Approach

The target of this study has been comparing CAV and VAV systems considering initial and operating costs together. For this purpose, a sample building located in Adana, which has a hot and humid climate during summer has been selected. The gross area of the building is 1628 m^2 and the outside surfaces of the walls are light colour. Long sides of the building face to the north and the south.

Two different uses of the sample building (as a school or as an office centre) and two different operating scenarios for the air-conditioning system have been considered. The operating times of the building and the air-conditioning system have been considered as between 8:00 and 17:00 h for scenario (1) and between 8:00 and 24:00 h for scenario (2). Life-cycle cost (LCC) analysis has been performed using detailed load-profiles, and initial and operating costs to evaluate the economic feasibility of CAV and VAV systems.

Conclusion of this research

With the results generated, It has been concluded that the present-worth cost of the VAV system is always lower than that of the CAV system at the end of the lifetime for all the cases considered. If the number of operating hours of the building is longer (scenario 2), the extra investment of the VAV system with respect to the CAV system pays itself back after approximately 4 years and in such a case the VAV system is a very economical choice for air-conditioning. In contrast, the VAV system is not economical with shorter operating hours (scenario 1). In this case, the payback period of the investment on VAV system with respect to the CAV system is always higher than 10 years.

2.2.4 Research 04

[Mohsen Soleimani-Mohseni1, Bertil Thomas. “A study of Demand Controlled Ventilation (DCV) and Constant Air Volume (CAV) systems.” Post graduate research, Dept. of Building Services Engineering, Chalmers University of Technology, Sweden, 2005.]

Approach

In this study, ventilation system in a room has been modelled by the following simple dynamic differential equation.

$\underline{V}.C_{out} + G - \underline{V}C_e = V\,dC/dT$ ———— (2)

Where, $\underline{V}$ is the rate of outside air flow, C_{out}, C_e and C are outdoor concentration, exhaust concentration and indoor concentration of CO_2 respectively, V is the volume of the building and G is the indoor pollutant generation rate.

The model has then been used for simulations. Different control strategies have been investigated and compared to the traditional base/forced ventilation systems.

Conclusion of this research

With the results, they have concluded that demand controlled ventilation using feedback system requires less integrated outdoor air flow in order to maintain an accepted air quality (no matter which controller is used) than base/forced ventilation.

To illustrate the saving, they have given a simple calculation.

The highest saving between of demand-controlled ventilation with variable outdoor air flow rate and CAV-system with a constant outdoor air flow rate on 0.9 m^3/s is 1664 m^3 during 45 minutes according to the simulation results.

In order to maintain an acceptable thermal comfort in a building, the supply air has been handled (by warming, cooling, humidifying etc).

The energy required to warm or cool 1664 m^3 outdoor air 10 °C during winter and summer respectively therefore,

ρ air · Cpair ·1664 · 10 = 1.2 · 1000 · 1664 · 10 = 20 MJ corresponding 5.5 kwh

Where, ρ air = Density of air [kg/m3]

Cpair = Specific heat capacity of the air [J/kg °C]

The saving has been proved as 5,5 kwh in rough calculation.

2.3 Special study done on VAV systems installed in Sri Lanka

A special study was conducted to gather some knowledge about VAV systems installed in Sri Lanka, design concept behind that and how they have optimized selecting a VAV system over CAV.

Target -

1. Studying on the VAV systems installed in Sri Lanka.
2. Gathering information on the norms and thumb rules used by designers in VAV systems.

2.3.1 Project 1:Veritas Consumer Products Lanka (Pvt) Ltd, Katubedda.

Building description: Four story office and laboratory complex.

Building load: Office hours – 230 TR

Non Office hours – 40 TR

Table 2: System description

Space category	**Cooling**	**Cooling control**	**Ventilation**	**Ventilation control**
High occupancy areas like meeting rooms, offices and auditoriums	Ceiling cassettes	Zone Thermostat	Conditioned fresh air	Motorized damper controlled by CO_2 sensor. Can be considered as demand controlled ventilation.
Spaces at Level 2 – 24 hr working without much load variation	Air terminals	Constant volume	Air terminals	Constant volume
Spaces at Level 2 – office hrs working with much load variation	VAV terminals	Zone load	VAV terminals	Zone load
Labs with fume hoods	Ceiling cassettes	Thermostat	Conditioned fresh air	Motorized damper controlled by Zone load. Exhaust is controlled by fume hood.

Remarks:

The VAV terminals are pressure independent. No measure is taken to maintain minimum ventilation requirement.

2.3.2 Project 2: ICC head office building at Kollupitiya

Building description – 7 storey office building

Building load: Office areas - 220 TR

Pantries and lobbies – 25 TR

Office area of each floor has glass facades facing West at each floor and perimeter zones facing east and South. The purpose of using VAV is getting the benefit of part load situations arising with solar gain fluctuations. The VAV boxes used here are pressure independent. A minimum flow is maintained according to the space.

2.3.3 Project 3: Hatton National Bank regional office, Jaffna

Building description - 4 storey office building. 03 typical office floors and auditorium at fourth floor.

VAV boxes have been prevalently used to respond for load variations due to solar gain and occupancy in office areas and demand controlled ventilation using a CO_2 sensor has been used for the auditorium.

2.3.4 Project 4: Mercedez – Benz centre

The building consists with a double height show room, customer waiting area and tea – Coffee shop. All areas are fed through VAV boxes to respond their high load variations. All VAV boxes are pressure independent type. Single duct VAV boxes and multi outlet VAVs are used.

2.3.5 Noted facts about VAVs with above case studies

In a room that the cooling load mainly fluctuating with occupation (i.e an assembly area or auditorium in a core zone), the fresh air problem in part load condition is minimum. The problem is complex when the room load is substantially fluctuating on both external heat gain and internal load. If external load factor is reduced at particular time of the day and occupation remains unchanged the part load air flow will starve the room with lack of fresh air.

Therefore, if the building is going to have a VAV system, it is desirable to locate meeting rooms, auditoriums at the building core rather than in perimeter zone.

When VAV is used, following costs are added to the initial cost of the system

VAV boxes – the amount of VAV boxes depends on the zoning pattern of the building.

<u>Additional thermostats</u> – In a CAV system, an AHU is controlled by a single thermostat. But in VAV, there can be few zones under single AHU and each zone is controlled by its thermostat.

<u>Increase of gauge of the ducts</u> – When part load occurs, the VAV boxes regulate to low flow rate and suddenly this increase the pressure of the duct system. Then the pressure transducer gives the signal to VSD unit of the AHU motor to modulate the speed. As this process takes few seconds, the duct system should be designed to tolerate a higher pressure than in CAV systems.

2.3.6 Some rules of thumb used by VAV designers

- In duct designing for a VAV system, static regain method is more advisable
- Pressure transducer should be mounted at a 2/3 distance from the supply fan

3.0 RESEARCH METHODOLOGY

02 medium rise office buildings were selected for the purpose. First one is Sports Ministry building (building 01) located at Reid Avenue, Colombo 07 which is a five storey building comprising 08 office areas. Second one is head office building of central engineering consultancy bureau (building 02) located at BauddhalokaMawatha, Colombo 07 which is a 7 storey office building. This building has 02 wings as Mahaweli and Kelani.

TRACE 700 Air Conditioning and design analysis software is used to carry out modelling, Energy and Economic Analysis of Air Conditioning system of above two buildings on the prospect of optimizing the using of Variable Air Volume system (VAV) over Constant Air Volume system (CAV) under current Electrical Tariff Structure of Ceylon electricity Board.

Following is the functional diagram of TRACE 700.

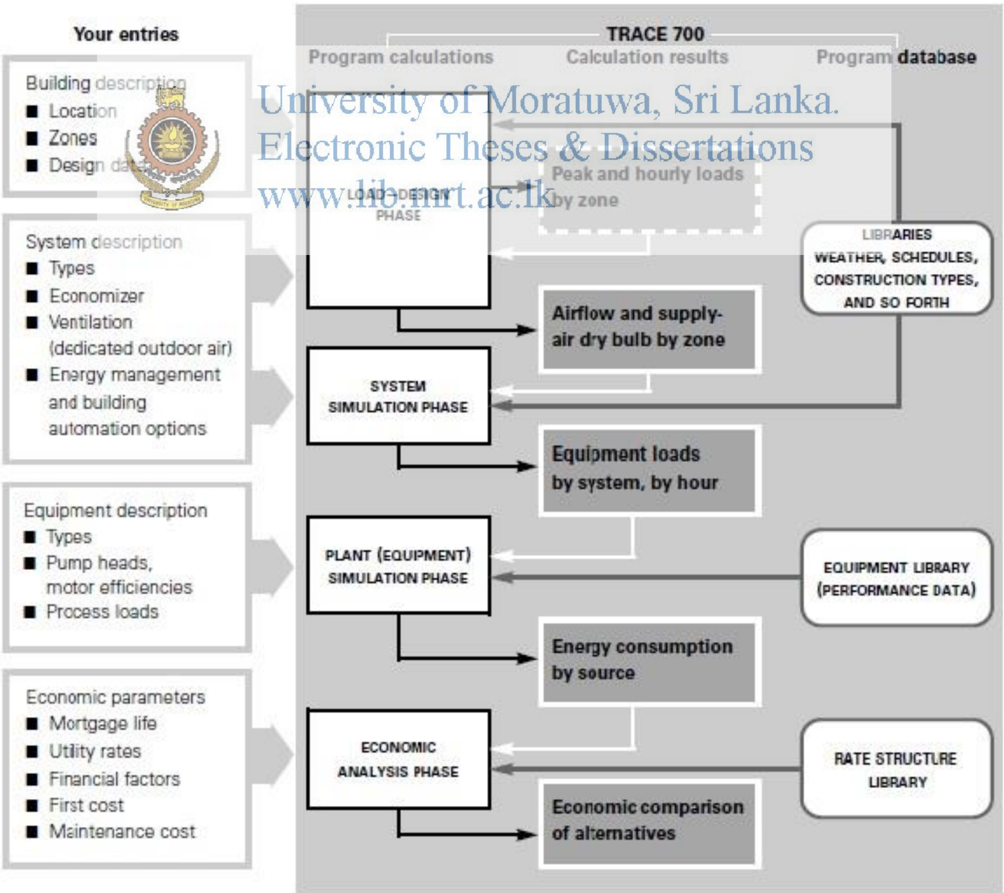

Figure 9: functional diagram of TRACE 700
[Trane Company. "Energy Modelling with TRACE 700," presented at Trane technical session, Colombo, Sri Lanka, 2014.]

Both buildings operate in normal working hours of 08.00 am to 05.00 pm. Building 01 was modelled as 68 spaces which are actually exist as separate spaces. Building 02 was modelled as 35 spaces but actually it has only 20 geometrically partitioned spaces. For the ease of zone allocation, the spaces which have 02 opposite external walls in more than 10 metre span were divided in to 2 spaces. For example, office space 01 of 3rd floor at Mahaweli wing (noted in model as 3FM office 1) is a single office space which has no internal partitions and has 2 external walls oppositely (one is faced to North West direction and other is to South East direction) at a span of 10 metres. This space was modelled as 2 spaces (noted in model as 3FM office 1 NW and 3FM office 1 SE). The modelling was done using few occupancy schedules for the comparison.

In air side systems modelling, 02 types of systems were created. One is constant air volume (alternative 01) and second is variable air volume. (Alternative 02) Similar number of air handling units (AHUs) was created for both alternatives. Following diagram shows the sequence of assigning the spaces to the AHUs.

Alternative 01

Alternative 02

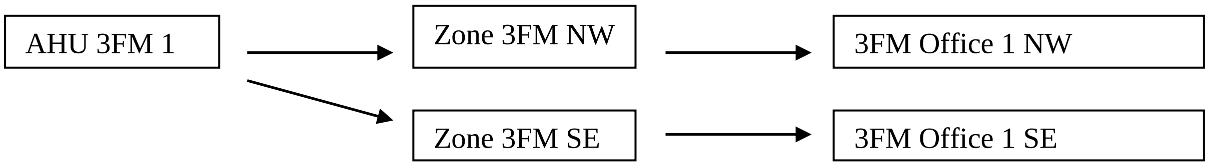

Figure 10: Sequence of assigning the spaces to AHUs

In alternative 01, single AHU caters single zone and all the spaces under that AHU was assigned to that zone. A thermostat at the return duct controls the chilled water flow to the AHU and hence the capacity was controlled.

In alternative 02, one AHU can be divided into few zones as suitable and each zone was assigned single or few spaces. Each zone was fed through a VAV box and a thermostat located in the zone area controls the air flow to the zone at the VAV box.

Both systems were assigned to a chillier plant of similar features. The economic life cycle analysis was carried out taking the constant air volume system as base case. The potential of using VAV systems over CAV systems was analysed from the economic analysis reports generated by the software using following electricity tariff structure of Ceylon Electricity Board.(General purpose customer category 2).

Customer Category G-2

This rate shall apply to supplies at each individual point of supply delivered and metered at 400/230 Volt nominal and where the contract demand exceeds 42 kVA.

Table 3: CEB tariff structure of customer category G-2

Time Intervals	Energy Charge (LKR/kWh)	Fixed Charge (LKR/month)	Maximum Demand Charge per month (LKR/kVA)
Peak (18.30-22.30)	26.60		
Day (5.30-18.30)	21.80	3,000	1,100
Off-Peak (22.30-05.30)	15.40		

4.0 ANALYTICAL FRAMEWORK

The focus on this research is analysing the feasibility and economic viability of using variable air volume system over constant air volume system as the air side building of a mid rise office building.

Both the buildings selected were medium rise office buildings (medium rise building is a building having height between 18m and 30m [Institute for Construction Training and Development. "Fire Regulations". Sri Lanka. ICTAD/DEV/14. Dec 2006]) operate between 8 am to 5 pm. In Sri Lanka, peak Electricity demand occurs between 6.30 pm to 10.30 pm. Therefore, normal operation of this building avoids the peak hour.

The internal conditions to maintain within the building are as follows:

Temperature: 23 – 25^{0}C

Humidity: 50 – 55 %

The analytical framework of this research is confined to study the potential of usability of a VAV system for building 01 and building 02 which can be extended to a guideline in selecting a suitable air system for a HVAC system in various magnitudes.

The comparison is done between 2 alternatives named as alternative 01 and alternative 02. Alternative 01 which is the base case is single zone CAV system. It is an air handling unit controlled by a single system level thermostat. Although it serves for few spaces, the conditions of each space cannot be individually controlled which makes thermally unsatisfied users in some spaces. Alternative 02 is VAV system which has zone level controlling strategy.

VAV systems are available in TRACE 700 in following various types and strategies such as, By pass VAV, Change over by pass VAV, parallel or series fan powered VAV, dual duct VAV, VAV with base board heating etc. For the analysis, it is selected "variable volume reheat (30% minimum default)" and the reheat coil was disabled in modelling. 30% of minimum flow is kept as a solution for indoor air quality problem in low load conditions. The supply air conditions are psychometrically selected in simulation. The supply fan cycling was selected to cycle with cooling loads only. All the heating coils are disabled.

5.0 COMPUTER MODELLING AND SIMULATION OF BUILDING 01 AND BUILDING 02 USING TRACE 700

Building description

Building 01

Building 01 is a 5 storey office building. Lobby area is at centre of 02 office spaces besides. Foot print area of the building is 1060 m^2. The floor to floor height of each floors are as follows;

Ground floor: 3.6m (H)

1^{st}, 2^{nd}, 3^{rd} floors: 3.3m (H)

4^{th} floor: 4m (H)

Building 02

Building 02 is a 6storey office building consisting 02 wings namely Mahaweli and Kelani. Foot print area of the building is 750 m^2. The floor to floor height of each floors are as follows;

Ground floor: 2.6m (H)

1^{st} floor: 2.6m (H)

2^{nd}, 3^{rd}, 4^{th}, 5^{th}, 6^{th}, 7th floors: 3.3m (H)

8^{h} floor: 4m (H)

Building Elements:

Floor: 150 mm concrete

Roof Slab at each floor:

Walls: 200 mm common brick 19 mm plaster on both sides

U-value of walls: 1.9559 $W/m^{2\,0}C$

Windows: triple coated glass

Doors: Aluminium Doors

Roof: Colour Bond Zn/Al roofing sheet with 25 mm insulation.

U-value of roof materials: 0.7082 $W/m^{2\,0}C$

Building orientations

Building 01

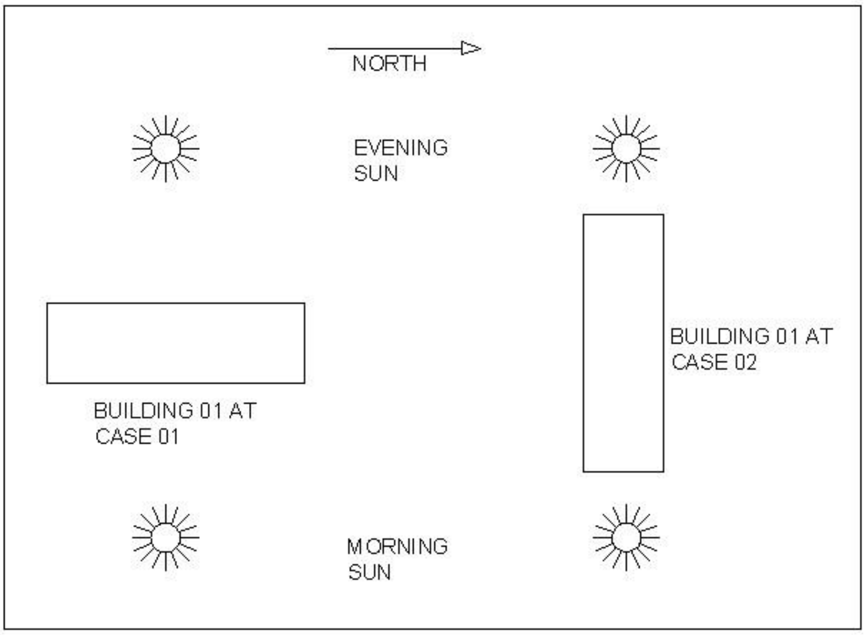

Figure 11: Approximate orientation of the building 01, at case 01 and case 02 relative to the North

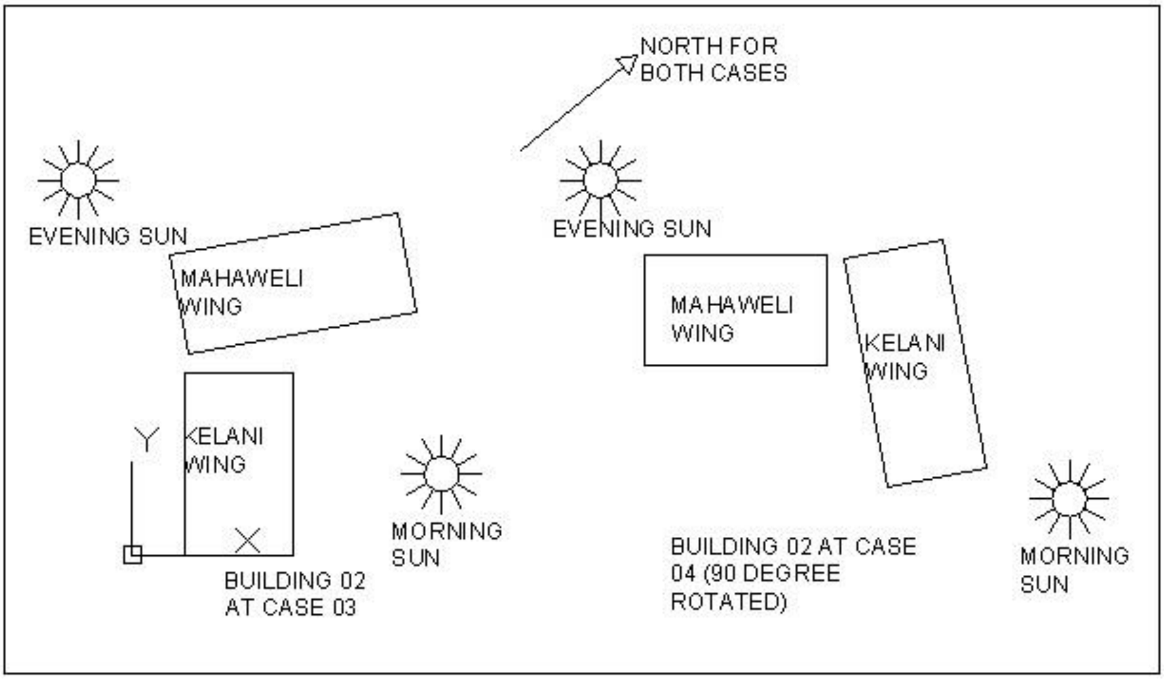

Figure 12: Approximate orientation of the building 01 at case 01 and case 02 relative to the North

Ventilation Requirements: ASHRAE 62.1

Conditions to be maintained inside office areas:

Dry bulb Temperature: 24^0C – 26^0C

Relative humidity: 50% to 60%

Conditions prevail in lobby areas are taken as ambient conditions.

Outside Conditions:

Dry bulb Temperature: 32^0C – 34^0C

Relative humidity: 80% to 85%

The rooms/zones can be created within the building with TRACE 700. The dimensions of floors, walls, roofs, doors and windows, orientation of walls, internal conditions/loads, ventilation requirements, construction materials etc of each room/zone within the building were input to the software and selected the weather file for Sri Lanka which was imported to TRACE 700.

Occupation schedules

Following occupation schedules were considered for the office spaces.

Schedule 01

Table 4: Occupant schedule 01

From	To	Occupation percentage
Midnight	7 a.m.	0
7 a.m.	8 a.m.	30
8 a.m.	5 p.m.	100
5 p.m.	6 p.m.	30
6 p.m.	7 p.m.	1
7 p.m.	Midnight	0

Schedule 02

Table 5: Occupant Schedule 02

From	To	Occupation percentage
Midnight	7 am	0
7 am	8 am	30
8 am	11 am	100
11 am	Noon	80
noon	1 pm	40
1 pm	2 pm	80
2 pm	5 pm	100
5 pm	6 pm	30
6 pm	9 pm	10
9 pm	midnight	5

Rooms/Zones assignment for air side systems:

Table 6: Room / Zone assignment for air side

Building	**Alternative**	**No of AHUs**	**No of FCUs**	**No of Zones**
Building 01	Alternative 01	8	1	8
	Alternative 02	8	1	42
Building 02	Alternative 01	19	0	19
	Alternative 02	19	0	35

In alternative 01, each AHU is considered as single zone. In alternative 02, each AHU has few zones.

The following cooling plants have been selected to meet the system requirements.

No/Type of Chillers: 01 number Rotary screw type chiller

Chiller Arrangements: Single Chiller arrangement with primary chilled water pump having three-way motorized valves for air handling units.

The given data were simulated to get the equipment capacities because the economic simulation requires installation cost and initial cost which should be determined with equipment capacities. In simulation, each building is simulated at two orientations as real orientation and 90 degree rotated clockwise orientation to create 04 cases for comparison as follows;

Case 01 - Original orientation of Building 01

Case 02 - 90 degree rotated clockwise of Building 01

Case 03 - Original orientation of Building 02

Case 04 - 90 degree rotated clockwise of Building 02

Economic Parameters used for computer modelling and simulation:

Study Life: 20 years

Cost of capital: 10%

Tariff Structure used for simulation:

(i) General purpose customer category G-2

Fixed charge –	LKR 3,000
Energy consumption -	peak – LKR 26.60
	Mid peak – LKR 21.80
	Off peak – LKR 15.40
Maximum demand-	LKR 1,100.00

(1US$ = LKR 131.00)

The computation of Installed Cost and Yearly Maintenance Costs are enclosed in Appendix-A.

The reports, tables and graphs generated from the TRACE 700 software is enclosed in the Appendix-B.

The Architectural drawings of the building 01 and building 02 enclosed in Appendix - C

6.0 SUMMERY AND OBSERVATIONS OF RESULTS

6.1 Equipment capacities

Case 01 – Building 01 in original orientation

Table 7: Equipment capacities of case 01

Equipment	**Alternative 1**(kW)	**Alternative 2**(kW)	**Percentage reduction in capacity**
Chiller plant	223.4	200.6	10.2%
AHU GFR	16.1	14.8	8%
AHU 1FL	22.6	20.1	11%
AHU 1FR	18.7	17.9	4.2%
AHU 2FL	31.1	29.9	3.8%
AHU 2FR	38.8	34.8	10.3%
AHU 3FL	30.1	30.2	-0.003%
AHU 3FR	29	22.7	21.7%
AHU 4FR	34.8	28.1	19.2%
FCU 1	2.2	2.2	0%

Case 02 – Building 01 in 90 degrees rotated clockwise orientation

Table 8: Equipment capacities of case 02

Equipment	**Alternative 01**(kW)	**Alternative 02**(kW)	**Percentage reduction in capacity**
Chiller plant	210.1	191	9%
AHU GFR	15	14.6	2.6%
AHU 1FL	20.4	18.6	8.8%
AHU 1FR	16.6	16	3.6%
AHU 2FL	29.9	27.2	9%
AHU 2FR	36.7	33.7	8.1%
AHU 3FL	28.6	27.1	5.2%
AHU 3FR	28.5	23.5	17.5%
AHU 4FR	32.3	28.2	12.7%
FCU 1	2.2	2.2	0%

Case 03 - Building 02 in original orientation

Table 9: Equipment capacities of case 03

Equipment	Alternative 01	Alternative 02	Percentage reduction in capacity
Chiller	206.4	189.8	8.04%
AHU 1FK	8.6	8.6	0%
AHU 3FK	13.8	13.1	5.07%
AHU 2FM2	9.1	7.7	15.38%
AHU 2FK	13.9	13.1	5.62%
AHU 2FM1	13.9	13.1	5.82%
AHU 4FK	13.8	13.1	4.80%
AHU 3FM1	11.8	10.6	10.25%
AHU 3FM2	8.9	7.6	14.80%
AHU 5FK	13.7	13.1	4.52%
AHU 6FK	13.7	13.1	4.24%
AHU 4FM1	12.1	10.6	12.03%
AHU 5FM1	12.0	10.6	11.52%
AHU 6FM1	11.9	10.6	11.15%
AHU 4FM2	8.9	7.6	14.32%
AHU 5FM2	10.5	10.4	1.23%
AHU 6FM2	8.8	7.6	13.34%
AHU 7FM2	8.6	7.3	15.31%
AHU Lib	8.3	8.2	0.85%
AHU CR	4.2	4.2	0%

Case 04 – Building 01 in 90 degrees rotated clockwise orientation

Table 10: Equipment capacities of case 04

Equipment	**Alternative 01**	**Alternative 02**	**Percentage reduction in capacity**
Chiller	206.1	190.0	7.83%
AHU 1FK	7.9	7.9	0%
AHU 3FK	13.5	13.0	3.56%
AHU 2FM2	9.2	8.3	9.88%
AHU 2FK	13.6	13.0	4.06%
AHU 2FM1	13.9	12.7	8.30%
AHU 4FK	13.4	13.0	3.20%
AHU 3FM1	11.8	10.6	9.79%
AHU 3FM2	9.3	7.5	19.09%
AHU 5FK	13.4	13.0	2.91%
AHU 6FK	13.4	13.0	2.69%
AHU 4FM1	11.9	10.6	10.77%
AHU 5FM1	11.8	10.6	10.25%
AHU 6FM1	11.8	10.6	9.79%
AHU 4FM2	9.2	7.5	18.48%
AHU 5FM2	11.4	11.1	2.37%
AHU 6FM2	9.1	7.5	17.49%
AHU 7FM2	9.0	7.2	19.82%
AHU Lib	8.9	8.8	1.12%
AHU CR	4.0	4.0	0%

Observations and remarks on equipment capacities

It is noted that the capacities of the equipment are reduced roughly by 10% if the air side system is changed from CAV to VAV. But in VAV system some additional equipment are added to the system such as VAV boxes, additional thermostats etc. Hence, the initial cost is a function of all these equipment. For example, in case 01 & 02, 42 VAV boxes and 34 additional thermostats are required for the system. In case 03 & 04, 35 VAV boxes and 16 additional thermostats are required.

6.2 Energy consumption

Energy consumption was analysed for 2 different occupation schedules. (Schedule 01 & schedule 02) Total building energy consumption = lighting + space heating + space cooling + heat rejection + pumps + fans + receptacles

When energy consumption is considered in the results generated, it is noted that the parameters lighting energy, space heating and receptacles are identical for 2 alternatives in each case. Therefore only the parameters which differentiate are considered.

6.2.1 Annual Energy Consumption for space cooling

Table 11: Energy for space cooling for each case at schedule 01

Case	**Alternative 01 (kWh/yr) x 10^3**	**Alternative 02(kWh/yr) x 10^3**	**Percentage saving (%)**
Case 01	90.2	89.3	1%
Case 02	77.3	76.1	1.6%
Case 03	130.7	115.2	11.9%
Case 04	130.4	112.1	14.0%

Table 12: Energy for space cooling for each case at schedule 02

Case	**Alternative 01 (kWh/yr) x 10^3**	**Alternative 02(kWh/yr) x 10^3**	**Percentage saving (%)**
Case 01	90.8	89.7	1.2%
Case 02	76.9	76.6	0.4%
Case 03	130.7	111.2	14.9%
Case 04	130.3	111.5	14.4%

6.2.2 Annual Energy Consumption for pumps

Table 13: Energy for pumps for each case at schedule 01

Case	Alternative 01 (kWh/yr) x 10^3	Alternative 02(kWh/yr) x 10^3	Percentage saving (%)
Case 01	57.2	61.4	-7.3%
Case 02	52.4	59.2	-13.0%
Case 03	44.4	41.5	6.5%
Case 04	44.5	39.4	11.5%

Table 14: Energy for pumps for each case at schedule 02

Case	Alternative 01 (kWh/yr) x 10^3	Alternative 02(kWh/yr) x 10^3	Percentage saving (%)
Case 01	61.3	61.2	0.2%
Case 02	55.7	58.6	-5.2%
Case 03	47.7	44.2	7.3%
Case 04	48.7	42.2	13.3%

6.2.3 Annual Energy Consumption for heat rejection

Table 15: Energy for Heat rejection for each case at schedule 01

Case	Alternative 01 (kWh/yr) x 10^3	Alternative 02(kWh/yr) x 10^3	Percentage saving (%)
Case 01	34.8	37.3	-7.2%
Case 02	31.9	36	-12.9%
Case 03	31.3	26.6	7.2%
Case 04	31.5	25.4	7.2%

Schedule 02

Case	Alternative 01 (kWh/yr) x 10^3	Alternative 02(kWh/yr) x 10^3	Percentage saving (%)
Case 01	37.3	37.2	0.3%
Case 02	33.8	35.6	-5.3%
Case 03	33.4	28.4	15.0%
Case 04	34	27.2	20.0%

Table 16: Energy for Heat rejection for each case at schedule 02

6.2.4 Annual Energy Consumption for fans

Table 17: Energy for Fans for each case at schedule 01

Case	Alternative 01 (kWh/yr) x 10^3	Alternative 02(kWh/yr) x 10^3	Percentage saving (%)
Case 01	93.4	9.7	89.6%
Case 02	71.8	8.7	87.9%
Case 03	59.5	13.5	77.3%
Case 04	73.1	17.3	76.3%

Table 18: Energy for Fans for each case at schedule 02

Case	Alternative 01 (kWh/yr) x 10^3	Alternative 02(kWh/yr) x 10^3	Percentage saving (%)
Case 01	93.3	9.2	90.1%
Case 02	72.2	8	88.9%
Case 03	59.6	13	78.2%
Case 04	73.1	17	76.7%

6.2.5 Annual Total Energy Consumption of the building

Table 19: Total Energy for each case at schedule 01

Case	Alternative 01 (kWh/yr) x 10^3	Alternative 02(kWh/yr) x 10^3	Percentage saving (%)
Case 01	403.6	325.6	19.3%
Case 02	361.3	307.9	14.8%
Case 03	406.9	337.6	17.0%
Case 04	420.5	335.1	20.3%

Table 20: Total Energy for each case at schedule 02

Case	Alternative 01 (kWh/yr) x 10^3	Alternative 02(kWh/yr) x 10^3	Percentage saving (%)
Case 01	410.6	325.3	20.8%
Case 02	366.6	306.8	16.3%
Case 03	412.3	337.6	18.1%
Case 04	427.1	338.8	20.7%

Observations

In all cases, fan energy has drastically reduced in alternative 02 for both occupation schedules. That means, VAV has a largest impact on fan energy. As a result, the total energy for VAV system has a reduction around 20%.

6.3 Cost analysis

6.3.1 Initial cost

Initial cost was calculated manually and the operating cost was calculated by TRACE 700 simulation tool. Real prices of the equipment were taken for the initial cost calculation.

It is noticed that the initial cost for alternative 02 depends on method of zoning and number of zones. In case 03 & 04, the number of zones is smaller and the cost increase from CAV to VAV is smaller. But in case 03 & 04, the energy saving is also very small between these alternatives. So, it is clear that there is a compromise between zoning pattern, number of zones and energy saving.

Following are the initial costs calculated;

Table 21: Initial costs for each case

Case	Alternative 01 (USD)	Alternative 02 (USD)	Percentage increase of the initial cost
01	303,101.79	357,230.15	17.9 %
02	300,455.34	354,362.96	17.9%
03	368,577.19	423,005.80	14.8%
04	368,589.30	419,111.60	13.7%

6.3.2 Annual Operating Cost

Table 22: Annual operating costs for each case at schedule 01

Case	Annual Operating Cost (USD)		
	Alternative 01	Alternative 02	Percentage saving (%)
Case 01	84,585	69,094	18.3%
Case 02	76,608	65,789	14.1%
Case 03	86,110	71,285	17.2%
Case 04	88,561	71,308	19.5%

Table 23: Annual operating costs for each case at schedule 02

Case	Annual Operating Cost (USD)		
	Alternative 01	Alternative 02	Percentage saving (%)
Case 01	86,118	69,653	19.1%
Case 02	77,756	66,296	14.7%
Case 03	88,248	72,221	18.2%
Case 04	91,170	72,504	20.5%

6.3.3 Life cycle cost for 20 years

Table 24: Life cycle costs for each case at schedule 01

Case	Life Cycle Cost (USD)		
	Alternative 01	**Alternative 02**	**Percentage saving**
Case 01	1,813,406.35	1,638,216.82	9.66%
Case 02	1,677,753.38	1,579,306.18	5.87%
Case 03	1,920,213.22	1,776,484.97	7.49%
Case 04	2,156,434.45	1,763,567.78	18.22%

Table 25: Life cycle costs for each case at schedule 02

Case	Life Cycle Cost (USD)		
	Alternative 01	**Alternative 02**	**Percentage saving**
Case 01	1,846,229.93	1,645,298.75	10.9%
Case 02	1,704,015.98	1,584,167.68	7.0%
Case 03	1,953,781.27	1,783,264.81	8.7%
Case 04	2,203,883.34	1,783,079.64	19.1%

6.3.4 Pay back periods of Alternative 02 over Alternative 01

Table 26: Payback periods of each case at schedule 01

Case	Simple payback	Life cycle pay back	Internal Rate of Return (IRR)
Case 01	3.8 years	4.3 years	34.4%
Case 02	5.5 years	6.5 years	25.1%
Case 03	4.1 years	4.8 years	31.8%
Case 04	3.1 years	3.1 years	48.3%

Table 27: Payback periods of each case at schedule 02

Case	Simple payback	Life cycle pay back	Internal Rate of Return (IRR)
Case 01	3.5 years	4.0 years	36.8%
Case 02	5.2 years	5.9 years	27.3%
Case 03	3.6 years	4.2 years	34.5%
Case 04	2.9 years	2.9 years	50.9%

6.3.5 Observations of cost analysis

- All cases except case 02 have life cycle payback periods less than 5 years.
- Case 04 is the most cost effective case.
- In every case, VAV is more effective for schedule 02.

6.4 number of cooling load unmet hours

In the TRACE 700 model, the schedules of equipment, people, ventilation, lighting etc were created to suit with normal office hours. But, the infiltration and miscellaneous scheduleshave some minor percentages in night hours because it is critical in determining the pull down load of the following day. That 24 hour schedules give a large amount of cooling load unmet hours in the results.

Table 28: Number of hours that cooling load not met for each case at schedule 01

Case	No of hours cooling load not met		Increase as a percentage (%)
	Alternative 01	Alternative 02	
Case 01	1,146	1,268	10.6%
Case 02	1,240	1,109	-10.6%
Case 03	1,502	1,957	30.3%
Case 04	1,370	2,116	54.5%

Table 29: Number of hours that cooling load not met for each case at schedule 02

Case	No of hours cooling load not met		Increase as a percentage (%)
	Alternative 01	Alternative 02	
Case 01	1,126	1,218	8.2%
Case 02	1,130	1,040	-8.0%
Case 03	1,502	2,079	38.4%
Case 04	1,370	2,033	48.4%

Only the case 02, which also has the longest payback period for VAV, has reduced the number of cooling load unmet hours by8-10% with introducing VAVfor both schedules. In case 04, which has the shortest payback period with VAV, the number of cooling load unmet hours has increased approximately by 50% in both schedules. But due to the results of case 01 and case 03, it is difficult to get a relationship between economic benefits and number of unmet hours of VAV.

6.5 Water consumption of the HVAC system

Table 30: Water consumption for each case with schedule 01

Case	Water Consumption (m^3)		Percentage Reduction
	Alternative 01	Alternative 02	
Case 01	2,174	2,183	-0.4%
Case 02	1,880	1,880	0.0%
Case 03	1,882	1,670	11.3%
Case 04	1,881	1,617	14.0%

Table 31: Water consumption for each case with schedule 02

Case	Water Consumption (m^3)		Percentage Reduction
	Alternative 01	Alternative 02	
Case 01	2,172	2,178	-0.3%
Case 02	1,861	1,878	-0.9%
Case 03	1,896	1,612	15.0%
Case 04	1,893	1,606	15.2%

Water consumption has remained almost equal for both alternatives in case 01 and case 02 (i.e for building 01). For case 03 and case 04 (i.e building 02), it has substantially reduced with using VAV systems.

6.6 Building a relationship to identify the usability of VAV with solar gain

For this analysis, two new parametersare defined as solar gain factor and occupancy diversity factor which are defined as follows;

Solar Gain Factor (SGF) = Heat gained by Solar Radiation / Total building load

Occupancy Diversity Factor (ODF)= $\frac{\Sigma \text{ (Percentage of occupancy x No of hours)}}{\text{Total AC operating hours}}$

For each case, SGF was calculated and Life Cycle Payback Period(LCPP) of using VAV against CAV of each four cases was plotted for both occupancy schedules.

Table 30: SGF and LCPP values for each case

Case	SGF	LCPP	
		Schedule 01	Schedule 02
Case 02	9.88	6.5	5.9
Case 03	13.85	4.8	4.2
Case 01	14.01	4.3	4.0
Case 04	16.17	3.1	2.9

Figure 14 illustrates the graph plotted taking SGF to 'x' axis and IRR to 'y' axis.

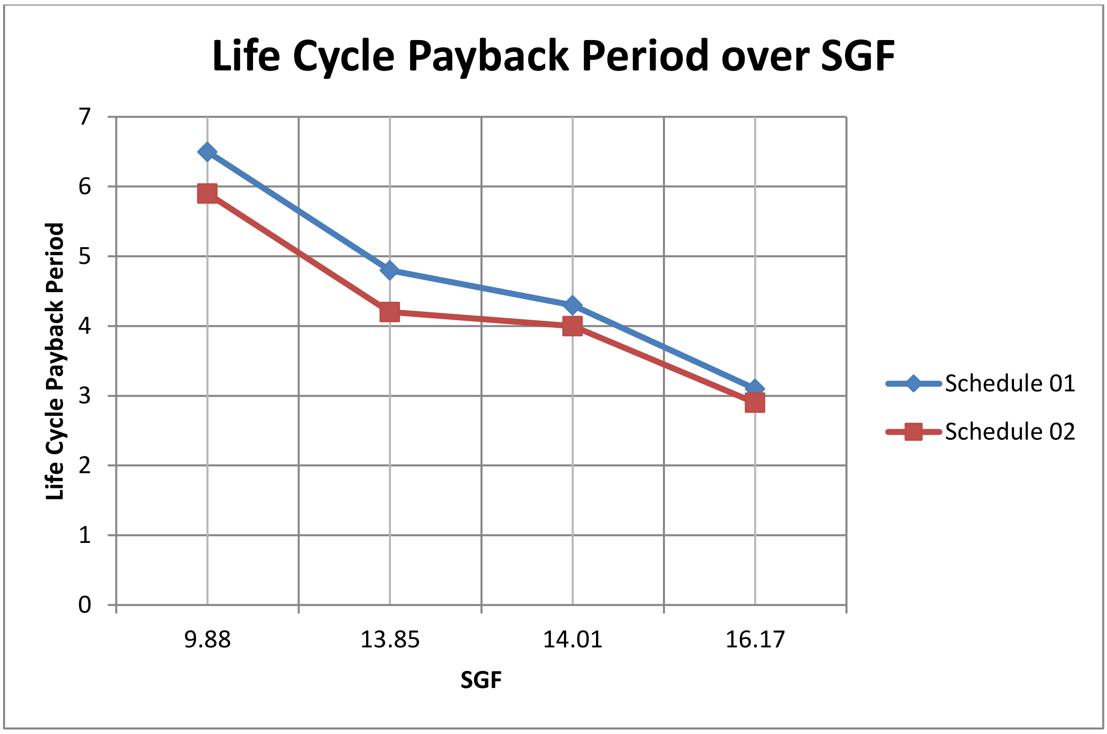

Figure 14: Graph plotted of Life Cycle Payback against SGF

For occupancy schedule 01, ODF = (1x30% + 9x100% + 1x30% + 1x 10%)/12 = **<u>80%</u>**

For occupancy schedule 02, ODF = (1x30% + 3x100% + 1x80% + 1x40% + 1x80% + 3x100% + 1x30% + 3x 10%)/14 = **<u>64%</u>**

Observations

- There is nearly a linear relationship between LCPP and SGF where we can define a benchmark for the usability of VAV systems against CAV systems for a considered type of building.
- The graph is offset to higher side when the occupancy schedule is more vary which is expected. But with this result, it can be observed that although the occupancy schedule is almost constant as in schedule 01 (ODF = 80%), there is a value of SGF, which gives a substantial payback of using VAV.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The main objective of this study was developing a guideline to select the most suitable air side technology between constant air volume (CAV) and variable air volume (VAV) for a mid-rise office building. For the study, two mid-rise office buildings were selected as building 01 and building 02 and modelled using TRACE 700 software for both CAV and VAV taking alternative 01 as CAV and alternative 02 as VAV.

The two buildings were modelled as to develop 04 cases as follows;

Case 01 – Original orientation of building 01

Case 02 – 90 degree rotated orientation of building 01

Case 03 – Original orientation of building 02

Case 04 – 90 degree rotated orientation of building 02

Each case was subjected to energy and economic simulation. Following observations were made after analysing the reports and graphs generated from TRACE 700 software.

1. Case 04 gains the highest cost benefit of using a VAV system for both schedules. The investment for VAV system is paid back in 3.1 years for schedule 01 and 2.9 years for schedule 02. Case 04 is developed by rotating the building 02 by 90 degree clockwise.

2. Case 01 gains the second highest cost benefit of using a VAV system for both schedules. The investment for VAV system is paid back in 4.3 years for schedule 01 and 4.0 years for schedule 02. Case 01 is developed by original orientation of building 01.

3. Case 03 gains the third highest cost benefit of using a VAV system for both schedules. The investment for VAV system is paid back in 4.8 years for schedule 01 and 4.2 years for schedule 02. Case 03 is developed by original orientation of building 02.

4. Case 02 gains the least cost benefit of using a VAV system for both schedules. The investment for VAV system is paid back in 6.5 years for schedule 01 and 5.9 years for

schedule 02. Case 02 is developed by rotating the building 01 by 90 degree clockwise. This building has the minimum solar gain fluctuation due to its orientation. (longer sides to North and East)

5. For all 04 cases, schedule 02 gains more benefit than schedule 01 by using VAV over CAV. For schedule 02, the highest payback period is 5.9 years and for schedule 01, the highest payback period is 6.5 years. Both are for same case.

6. There is a nearly linear relationship between Life Cycle Payback Period (LCPP) of using VAV over CAV and Solar Gain Factor (SGF). According to that relationship, for a building with an occupancy schedule like schedule 01(ODF = 80%), SGF should be over 13.4 to gain a payback period of 5 years and for a building with occupancy schedule 02 (ODF = 64%), the value is 11.9.

Following conclusions were reached with above observations;

Prior to the selection of the air system between CAV and VAV, the parameters SGF and ODF should be obtained which can be derived from basic cooling load calculation and some studies on occupancy variation of the building. Then with respect to the above defined benchmark values, it can be decided whether CAV or VAV is preferable. The ODF values of selected occupancy schedules here are 64% and 80%. In general, most of the midrise office buildings operate between these two values. Therefore, for an office building, SGF of 11.9 can be considered as a threshold value. For any exception which has ODF values lower than 64%, there may be a lower value for SGF. Hence, for any case beyond above ODF value range, this study should be extended.

When considering the number of cooling loads unmet hours, only one case has improved with VAV. Other cases have substantial increase of unmet hours. Also that is not a clear function of the financial performance. That means, the number of cooling load unmet hours is not predictable with this sample cases. It is case dependant. As most of these cooling load unmet hours occur in low occupied hours of the building, this is not a good indicator on the functionality of the system,

Although the initial cost of VAV is increased with additional equipment like VAV boxes, VSDs etc, the downsizing of the water side and air side equipment compensate some portion of the above increased cost. This downsizing of equipment can be clarified as follows;
Consider the time where peak load occurs. Although, at peak load time of the building, there are spaces in part load situations. The CAV system delivers the constant amount of supply air while the VAV delivers the amount relevant to the load of the space. The total airflow is always lower in VAV resulting lower amount of ventilation air through outdoor air damper. This results lower ventilation load on the AHU coil. But, with the equipment available in the market, this downsizing can be negligible.

When considering water consumption for cooling towers, it seems to be a function of the building with these 04 cases. More studies should be done with few more buildings on this matter.
In general, a midrise office building with highly fluctuating occupant load and significantly fluctuating external loads can be benefitted by using variable air volume systems over constant air volume systems despite the unpredictability of savings on water consumption and number of cooling load unmet hours which should be determined with a modelling and simulation tool at design stage.

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