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Mechanical Ventilation & Cooling Energy versus Thermal Comfort: A Study of Mixed Mode Office Building Performance in Abu Dhabi

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Abstract

In hot climates, office building ventilation and cooling dual operation can cause high energy consumption in order to maintain thermal comfort limits. Using mixed mode ventilation and cooling operation, incorporation of natural ventilation strategies can offer significant reductions in annual energy consumption. Natural ventilation operation can be used with an external air temperature ranging from 24 to 28°C. Within this paper, a literature on thermal comfort is completed to understand temperature limits for hot climates.

This work details theoretical model analysis of a simple mixed mode office building located in a hot climate, Abu Dhabi, United Arab Emirates. This is completed using dynamic thermal simulation. The aim of this work is to evaluate the impacts on mechanical ventilation and cooling energy when raising internal comfort temperatures beyond 24°C; to a maximum of 28°C. Time/temperature analysis is completed for different months of the year to ascertain when thermal comfort temperatures are exceeded and full mechanical operation is required. Results from this analysis show yearly ventilation and cooling energy savings ranging between 21-39% and demonstrate that higher mechanical cooling set point operations can be achieved when human occupants have access to openable windows.

Keywords: Natural Ventilation, Mixed Mode, Mechanical Cooling; Thermal Comfort, Openable Windows.

1 Introduction

In hot climates, excessive mechanical ventilation and cooling energy is a significant issue and considerable amounts of cooling is required during daytime periods to maintain indoor thermal comfort levels. In order to save energy, reduce carbon dioxide emissions and operational expenditure, alternative ventilation strategies and control methods should be adopted within the initial building design i.e. natural ventilation. Where office buildings are capable of mixed mode ventilation operation (CIBSE, 2000), thermal comfort set points can be increased to allow internal spaces to become warmer, hence reduce operation of mechanical services plant. This issue identified is thermal comfort parameters are compromised (CIBSE, 1999) i.e. exceed 22-25°C range. This paper provides an analytical assessment method to assess how mechanical ventilation and cooling energy can be reduced by increasing the internal thermal comfort set point temperature in a hot climate, Abu Dhabi, UAE. Using a theoretical office building model and Dynamic Thermal Simulations (DTS) tool, impacts of external supply air temperature are completed using time/temperature curve analysis. Percentage energy consumption can be predicted for natural ventilation operation (per year) and compared against base case model i.e. full time operation. The aim of this work is to understand maximum potential mechanical ventilation and cooling energy savings and discuss the impacts on office thermal comfort (adaptive), as defined by Brager & De Dear (2000).

The aim is realised by the following four objectives:

- Literature review of maximum tolerable temperatures for neutral thermal comfort.
- Develop an theoretical office building base case thermal model using dynamic thermal modelling software located in a Abu Dhabi and calculate cooling energy per month
- Using daily time/temperature analysis, determine natural ventilation and mechanical ventilation/cooling systems operation times
- Calculate potential percentage energy reductions for each set point temperature

2 Literature Review

As humans regularly adapt to their environment (Physiological, Behavioural and Psychological), a wider range of temperatures are more tolerable in naturally ventilated building (Brager & De Dear, 2000). The ability to open windows allows individuals to have control of their environment hence allow higher internal temperatures. Individual's tolerance is largely dependent on level of clo as analysed by Krzysztof & De Dear (2001) where individuals reported on thermal neutrality at 23.3°C. A literature review completed by Brager & De Dear (1998) highlighted that a study completed in Hong Kong suggests that individuals achieved thermal neutrality at 24.9°C. Furthermore a study completed by Humphreys discovered that depending where located in the world, tolerable thermal comfort temperatures can be 28.7°C (Malay Peninsular) and 25.7°C in London (Brager & De Dear, 1998). This builds a case for increasing the mechanical system set point temperature beyond recommended thermal conditions (CIBSE, 2015) hence increasing the mechanical ventilation and cooling set points to a higher value.

For control of an indoor environments, Iftikhar et al (2001) discovered that the most important factor was openable windows with drawn or half drawn blinds. This study shown extensive use of windows when internal temperature exceeds 20°C with 100% windows open at 27°C. Furthermore, De Dear & Brager (2002) define building scope for naturally ventilated space cooling as openable windows should be ease and access as primary means of thermos-regulation and cannot have a mechanical cooling systems.

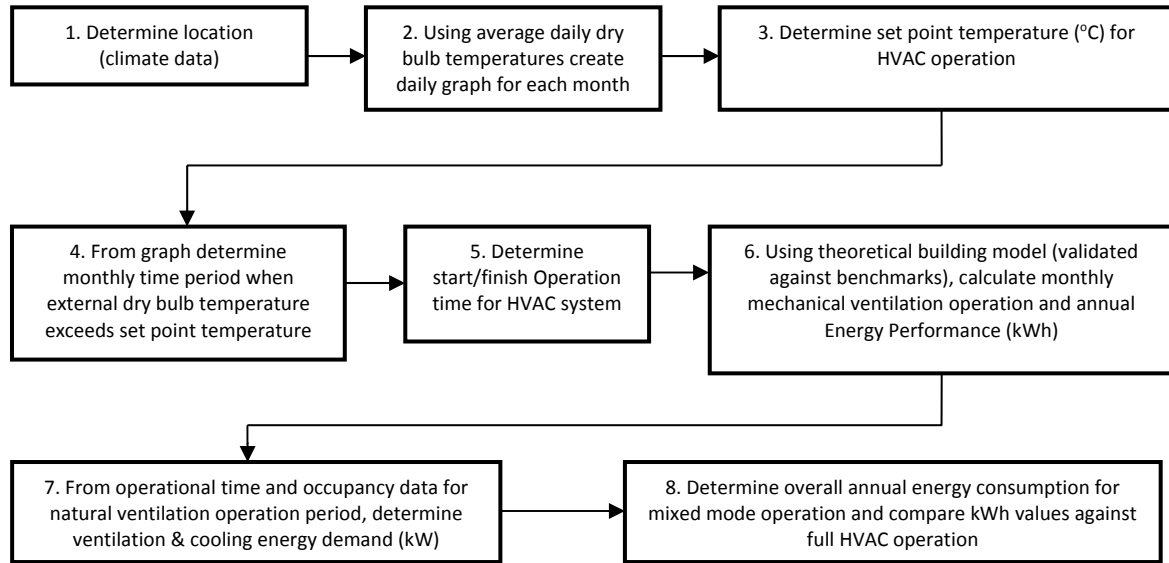
Guidance is also set out in British Standard (2005) when attempting to calculate PMV vs PPD however the calculated percentage dissatisfied may be higher than actual hence adaptive approach is better suited to this study.

3 Methodology

3.1 Mixed Mode Operation Performance Assessment

This section review the impacts of increasing HVAC set point be increasing thermal comfort level from 24°C to 28°C. For each temperature the time period is taken from the graph and converted into energy for each month assuming 100 percent fresh air for both modes of operation. This method of performance assessment is shown in Figure 1 below.

Figure 1. Mixed Mode Performance Assessment Methodology Flow Diagram



This flow diagram has been created to develop a new approach for assessing natural ventilation effects on reducing HVAC performance by calculating time external dry bulb air temperature exceeds HVAC set point. The time periods will determine HVAC times of operation between each mode. The amount of energy saved by varying set points can be used to calculate ventilation and cooling energy consumption. To calculate total time save, the following correlation applies:

$$QV_{(t)} = MV_{(t)} - NV_{(t)} \quad \text{Eq. 1}$$

Where; $QV_{(t)}$ is total time reduction available at a given time period, $MV_{(t)}$ is full time operational time of mechanical ventilation system in hours and $NV_{(t)}$ is operational time of natural ventilation in hours.

The building ventilation strategy is mixed mode where base case HVAC operation temperature is set when internal air temperature exceeds 24°C using 100 percent fresh air delivery for both modes. HVAC operational time is detailed below in Table 1.

Table 1. Office Operational Hours

Hours of Office	Pre-cool Period	Office Closing	Total office Hours for Day
Start (Time)	Time (Hours)	Start (Time)	Time (Hours)
0800	1	1800	11

3.2 Theoretical Building Model

A theoretical commercial building model was created and dynamic thermal simulations were completed to calculate room cooling load (kW) over a yearly period. The building is single height open office plan (theoretical model) has been created 20m (L) x 10 (W) x 3m (H) with a flat roof. Figure 2 shows graphic of building.

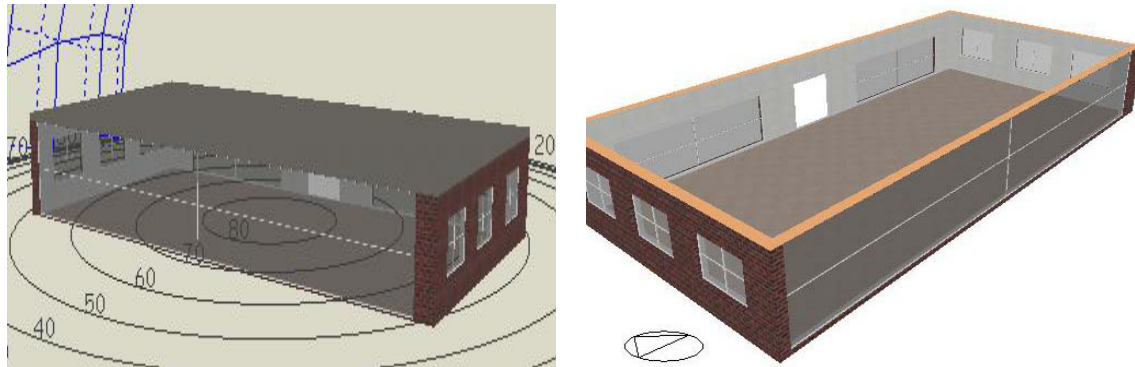


Figure 2. South View of Office Building & South South West View of Office Building illustrating interior (Graphic)

The south façade consists of a full height window 3m (H) x 19m (W). The East and West walls contain 3No. 2m (W) x 1.5m (h) and North wall contains double doors which are 2m (H) x 1.9m (W) and 2No. windows 6m (W) x 2m (H). The graphic generated by the software is shown in figure 2 below which shows the South facade view. Figure 3 indicate the building without the flat roof show highlighting the interior. The test building is based upon a generic building design identified by 1 North Bank, Sheffield, Yorkshire (e-architect, 2014). The metrics used (SI Units) in this analysis are mechanical cooling input energy consumption (kWh), sensible cooling load (kW) and Latent Heat Gains (kW). Sensible and latent heat gains are combined to determine annual mechanical cooling energy. For building parameters, see Table 2 below.

Table 2. Building Parameters

Type	Description
External Walls	Brickwork, Outer Leaf (105mm), XPS Extruded Polystyrene (118mm), Medium Concrete Block (100mm) & Gypsum Plastering - U value of 0.25W/m ² K
Roof (Flat)	Asphalt (10mm), MW Glass Wool (200mm), Air Gap (200mm), Plasterboard 13mm- U Value of 0.186W/m ² K
Floor	Urea Formaldehyde Foam (200mm), Cast Concrete (100mm), Floor Screed (70mm) & Timber Flooring (30mm) - U Value of 0.176 W/m ² K
Glazing	Pilkington North America Solar-E Arctic Blue (7.9mm), 12mm Argon Filled Gap & Pilkington North America Eclipse Advantage Clear (5.91mm)- U Value of 1.685W/m ² K
Doors	Metal Framed Doors with Infill to match glazing- Pilkington North America Solar-E Arctic Blue (7.9mm), 12mm Argon Filled Gap & Pilkington North America Eclipse Advantage Clear- U Value of 1.685W/m ² K
Air Permeability	0.25 Air Changes Per Hour
Ventilation	Normal Operation (Base Case)- 10 litres/second per person Supply Air condition 12°C Supply Air Humidity Ratio (g/g)- 0.08 Vents for Natural Ventilation- Large Grille (Dark Slates)- 0.5 Co-efficient of Discharge
Indoor Environmental Conditions (Summer Time Cooling)	Nominal Cooling-24°C Cooling Set Back- 26°C
Internal heat gains are based on occupancy and lighting heat gains only	Lighting – 12W/m ² Occupancy Density- 10m ² /Person Activity- Light Office Work/Standing/Walking Computers 25W/m ² Other Equipment- 0W/m ² (Non Selected)
Mechanical Cooling Fuel Source	Electrical

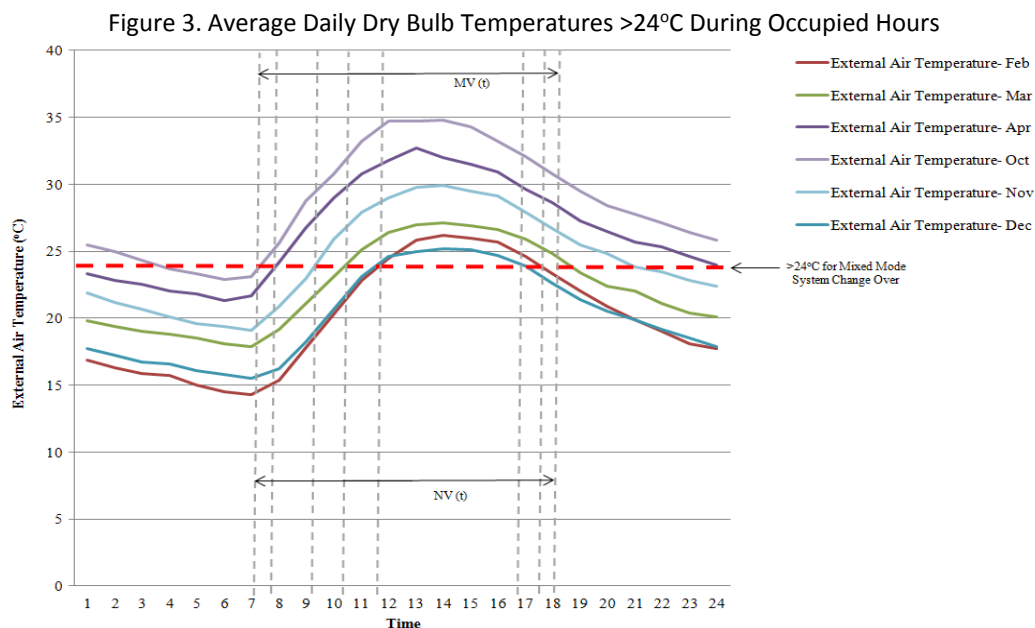
The building is simulated using Design builder software version 3.0.0.105 incorporating DB Sim v1.0.2.1 as this enables dynamic thermal building simulations for mechanical cooling loads and input energy required for the cooling system operation over monthly and a yearly

period. Climate data used is Design Summer Year (DSY) data within DesignBuilder. The building location selected is Abu Dhabi, UAE, as this provides one global extreme of a hot climate. A solution algorithm of finite differencing and adaptive convection algorithms are used for interior convection including McAdams algorithm used for exterior convection. Within the simulation air velocities for comfort are 0.1370 m/s.

4 Time/Temperature Analysis

Natural ventilation mode is in operation when external air temperature is less than the internal space set point temperature. Where external air temperature exceeds the set point temperature (24-28°C), mechanical ventilation/cooling mode is in full operation. For example, actuation conditions of natural ventilation where external dry bulb temperature does not exceed internal set point temperature ($T_o < SP$). Once the set point temperature is exceeded, HVAC operation ($T_o > SP$) will activate. For mixed mode operation, energy consumption is revised accordingly as mixed mode system time periods change hourly hence operation and automatically adjusted accordingly via building energy management system (BEMS). The important factor is to determine the operational times for both modes of operation, which are mechanical ventilation operational time ($MV_{(t)}$) and natural ventilation activation time ($NV_{(t)}$).

To calculate the effects of timed operation of mechanical plant, time/temperature graphs are generated for hottest day in each month, see Figure 3 below. The plots show maximum average dry bulb temperature experienced using weather data from DesignBuilder software. A horizontal line is added for each set point temperature and time is identified on the graphs intersect point within the curve, start and finish points. $NV_{(t)}$ is identified below the horizontal set point line and $MV_{(t)}$ is above. The graph also detail where external air temperature for February, March, April, October, November and December exceeds internal set point temperature. From the calculations for January, theoretically the set point is not exceeded therefore HVAC operation would not be required, however this may not be the case in practice. For months that temperatures that clearly exceeds 24°C, full time HVAC operation is required.



The occupied office time period for natural ventilation operation ($NV_{(t)}$) and mechanical HVAC operation ($MV_{(t)}$) is taken from the graph (Figure 3) and revises base case HVAC energy consumption calculating total kilowatt hours per month, using corrected times detailed in Table 3. Normal HVAC operation for the base case is 11 hours per day ($MV_{(t)BC}$).

Table 3. Time Period for External Air Temperature Exceeding 24°C

Month	MV (t) Start	MV (t) Stop	Time Difference (Hours)	Occupied Hours (Converted)		Available Working Days For Month (Mon - Fri)
				MV (t)-Time	NV (t)-Time	
February	11:30:00	17:00:00	05:30:00	5.5	5.5	20
March	10:15:00	18:00:00	07:45:00	7.75	3.25	20
April	07:45:00	18:00:00	10:15:00	10.25	0.75	22
October	07:00:00	18:00:00	11:00:00	11	0	23
November	09:10:00	18:00:00	08:50:00	8.87	2.13	20
December	11:30:00	17:00:00	05:30:00	5.5	5.5	17

This method was applied for the remaining set point temperatures 25°C, 26°C, 27°C and 28°C. As the external air temperature increases natural ventilation operational time decreases; indirectly proportional.

5. Results

Using base case mechanical ventilation and cooling energy results, Figures 4 and 5 below shows energy performance values for mechanical fan energy/cooling energy of each external set point temperature base on the hours of natural ventilation operation ($NV_{(t)}$) deducted from mechanical ventilation operation base case model ($MV_{(t)}$). As shown from monthly energy profiles, increasing internal thermal comfort set point temperature has a significant impacts on reducing mechanical ventilation and cooling energy from February to April and October to December in Abu Dhabi. The graph also shows in all cases full mechanical ventilation is required for May to September.

Figure 4. Mechanical Ventilation Energy Reduction (Mixed Mode) for Mechanical Fan Energy

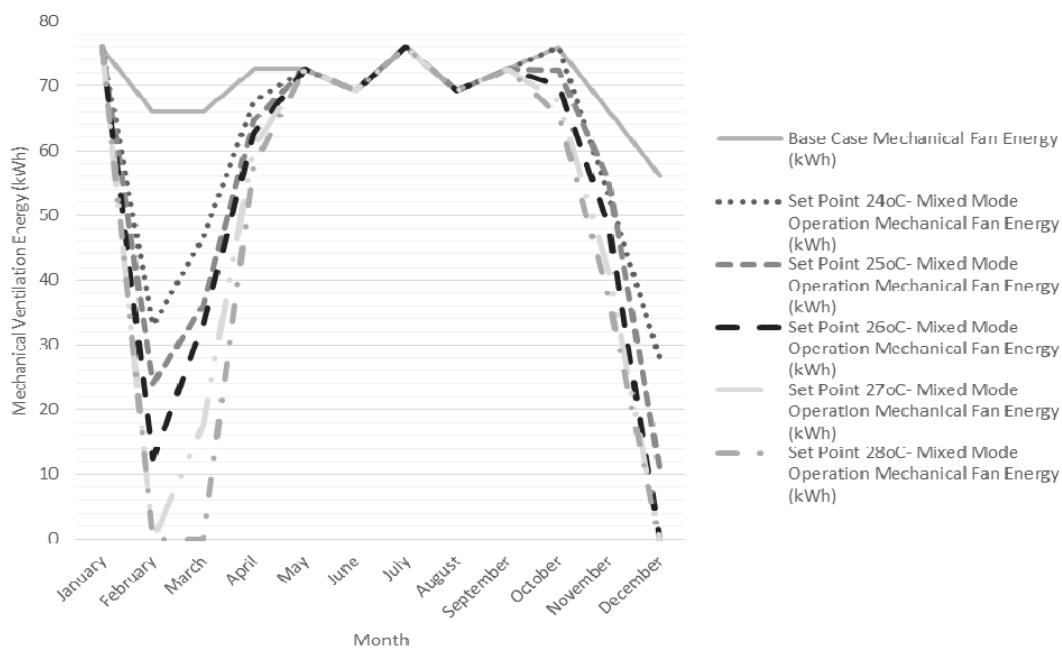


Figure 5. Mechanical Cooling Energy Reduction Using Mixed Mode Operation

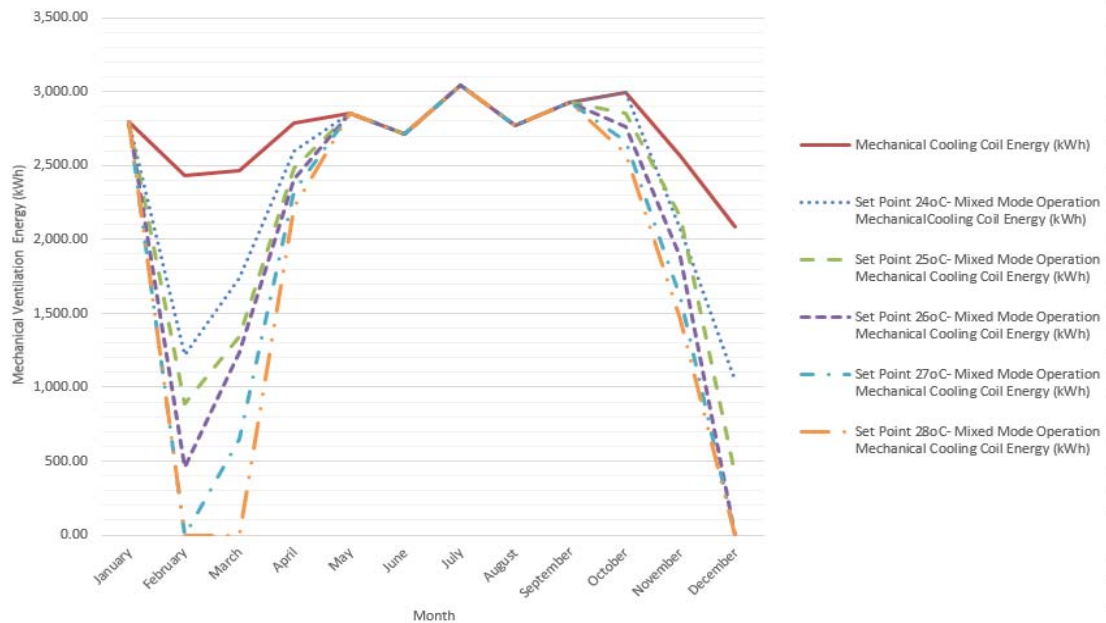


Table 4 below show calculated reductions that can be achieved. For Abu Dhabi climate, the greatest HVAC reductions for February and December by reducing the energy consumption by half.

Table 4. Percentage Reduction Using Mixed Mode Ventilation & Cooling at 24°C Set Point

Month	Total Ventilation and Cooling Plant Energy (kWh) for Mechanical Operation (Base Case)	Total Ventilation and Cooling Plant Energy (kWh) for Mixed Mode Operation (Hybrid)	Percentage Reduction Using Mixed Mode Operation
February	2,501.68	1,250.84	50.00
March	2,529.73	1,782.31	29.55
April	2,857.82	2,662.97	6.82
November	2,628.45	2,119.48	19.36
December	2,144.19	1,072.10	50.00

From the results highlighted in Figures 4 and 5, annual energy reductions can be determined as an average percentage (Table 5 below). The percentages expressed show the total amount of mechanical ventilation and cooling energy that can be saved.

Table 5- Annual Energy Reduction when Adapting Mechanical Ventilation Set Point Temperature

Month	Reduction (%) (SP<24°C)	Reduction (%) (SP<25°C)	Reduction (%) (SP<26°C)	Reduction (%) (SP<27°C)	Reduction (%) (SP<28°C)
% Reduction/Annum	21.31	26.72	31.57	36.53	39.77

The results show that adopting this method can achieve an energy reduction ranging from 21.31 to 39.77 percent.

4.1 Validation

The method of analysing natural ventilation and impacts of HVAC energy performance is completely unique in its approach. Validation proves somewhat difficult as many natural ventilation research conference papers, journal and books only review the performance of air flow, air temperature and heat gains. Inter-comparison of energy performance is difficult to empirically validate due to lack of readily available bias building HVAC performance data. This method of approximated time/temperature is a solid and fundamental approach that provides calculated effects of natural ventilation on mechanical ventilation and cooling

energy performance and operation. From this analysis, calculated monthly values can be used and compared against an actual building BMS system (monitored outputs) and provide a benchmark how the building should be performing.

6 Discussion

The results show that during cooler climatic months greater energy savings can be achieved. In summer time periods, energy reduction is minimal or not achievable. There are significant savings available when adopting natural ventilation temperature/time methodology and can be easily implemented within a RIBA design process (RIBA, 2016) and new/existing BEMS. In hot climates, energy reductions are only achievable in cooler months of the year as summer months would be considered intolerable for both humans and office equipment i.e. computers, photocopiers, printers. Natural ventilation however is limited to office spaces as communications rooms need 24 hour mechanical ventilation and cooling strategies.

When attempting to assess mechanical ventilation & cooling energy versus thermal comfort, difficult arise as each individual has different thermal comfort levels based on age, gender and metabolic rate. For example, hypothetically higher set points such as 26°C may be suitable for 60% of occupants and improve energy reduction but the remaining 40% will be considerable dissatisfied with their environment, hence lowering by 1°C can possibly reduce dissatisfaction to lower percentages, toward 5% dissatisfied (British Standard, 2005).

7 Conclusion

This study provides a new approach to estimating mixed mode ventilation and cooling energy performance using time/temperature assessment methodology. The results from the method highlight the following:

- Time/Temperature assessments allow suitable energy predictions for mixed mode operation and provide suitable information for engineers at RIBA Stage 2 (Concept design) and stage 3 (Developed Design) (RIBA, 2014).
- Energy savings identified by time/temperature analysis (natural ventilation operational time deducted from mechanical ventilation operation) time range between 21.31-39.77%. By increasing internal temperature set point temperature annual energy savings are identified in these percentages. Savings are generally realised during cooler months of the year in Abu Dhabi.
- As determined by the literature review, higher set points can be applied provided the building has openable windows with clear access.

It is important to note that a constant higher temperature i.e. greater than 25°C, will make the internal environment very uncomfortable for human occupation therefore the realistic values would a maximum set point temperature of 26°C.

8 Further Works

Possible future research could be completed is as follows:

- Integrate method within dynamic thermal simulation software
- Develop BEMS algorithms to enable close temperature control by closely monitoring external air temperature and dry bulb temperature associated pattern (sinusoidal).
- Validate calculated percentages against real building operation in hot climate.

- Apply to existing building energy management systems (BEMS) and measure the level of discomfort and compare against energy savings.

8. Nomenclature

BEMS	Building Energy Management System
CIBSE	Chartered Institution of Building Services Engineers
DTS	Dynamic Thermal Simulation
HVAC	Heating Ventilation & Air Conditioning
PMV	Predicted Mean Vote
PPD	Percentage People Dissatisfied
MV _(t)	Mechanical Ventilation Operational Time
NV _(t)	Mechanical Ventilation Operational Time
MV _{(t)BC}	Base Case Mechanical Ventilation Operational Time
°C	Degrees Celsius
kW	Kilowatt
kWh	Kilowatt-hour

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