AMERICAN UNIVERSITY OF BEIRUT

ASSESSING MIXED MODE COOLING IN LEBANON OFFICE BUILDINGS

by
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AN ABSTRACT OF THE THESIS OF

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The aim of this study is to assess the use of mixed mode ventilation for a typical office building in Lebanon, and consequently reduce Heating Ventilation and Air Conditioning (HVAC) energy consumption in the observed recent and under future climatic conditions. Mixed Mode cooling was thought of being a compromise between the insufficient natural ventilation and the expensive year round operated HVAC. A control algorithm is set for windows and HVAC system to ensure mixed mode operation. The results of the simulations were evaluated in terms of potential reduction in energy consumption under the present and the future weather data. Finally a lifecycle cost analysis was performed for the proposed system and its payback period was computed. Under present construction practices and weather data 31% annual energy savings were achieved using Mixed Mode system. Under future 2050's weather data 21% annual energy savings resulted with a payback period of 3.8 year.

CONTENTS

NOMENCLATURE

T_{OUT}	Outdoor Temperature (°C).
IES-VE	Integrated Environmental Solutions Virtual Environment (Design and Energy Simulation Software).
T_{UL}	Adaptive Cooling Upper Limit Set-Point Defined in the ASHRAE 55 Adaptive Comfort Model (°C).
T_{LL}	Adaptive Heating Lower Limit Set-Point Defined in the ASHRAE 55 Adaptive Comfort Model (°C).
T_{AC}	Mechanical system Air Conditioning set point temperature (°C).
T_{He}	Mechanical system heating set point temperature (°C).
U value	Overall Heat Transfer Coefficient (W/m²K).
Δt_m	Monthly mean change in temperature (°C).
IPCC	Intergovernmental Panel on Climate Change.
Δt_{mwb}	Monthly Mean bulb Temperatures (°C).
$\Delta T_{\max_m} - \Delta T_{\min_m}$	Diurnal Temperature (°C).
Δr_m	Relative Humidity (%).
$\Delta I_{h,m}$	Monthly Percentage Mean Change in Solar Irradiance

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CHAPTER I

MIXED MODE SYSTEM

A. Introduction

One major global concern nowadays is climate change and it was subject to numerous studies. These studies aimed at the quantification of future global weather trends. For example, the Intergovernmental Panel on Climate Change (IPCC) quantified an average global surface temperature increase of 0.9°C to 4.8°C by the years 2100’s under different CO2 emission scenarios (high emission, medium emission, low emission) (Alves et al. 2015). This surface temperature increase affects largely the buildings energy consumption.

Buildings consume currently 40% of the global energy consumption (Vorsatz et al. 2012) where offices represent one of the most energy intensive constructions (Lombard et al. 2008). Particularly in the Middle East, buildings consume 27% of the total energy consumption (Vorsatz et al. 2012, Lombard et al. 2008). This energy consumption is expected to increase at an annual rate of 3.2% in the Middle East (Lombard et al. 2008). The increasing energy consumption triggers several consequences as the depletion of global energy resources and the increase in Green House Gases (GHG) emissions. This brings the need to reduce energy consumption in office buildings in the present and future especially for HVAC systems due to its link to the outdoor weather conditions. To reduce HVAC energy consumption without implications on thermal comfort and indoor air quality, studies have assessed the use of passive systems such as natural ventilation and night ventilation instead of the conventional air conditioning systems to cool buildings (Pfafferott et al. 2004- Pollock et al. 2009). Natural ventilation was found promising in moderate climates for several types of buildings, and was found to reduce building energy consumption and offer an acceptable indoor environment (Pfafferott et al. 2004, Annan et al. 2014). In the Middle East, 52% possibility of natural ventilation usage was expected in Lebanon under current weather data (Annan et al. 2014) and around 10% to 40% energy savings were achieved in Dubai-UAE due to the use of natural ventilation in the moderate months (Taleb et al.2015).

In office spaces, workers productivity is crucial and thermal comfort should be sufficient. However for thermal comfort to be provided, natural ventilation is not sufficient all over the year and its use is limited to the moderate periods. This made the engineers hesitate to implement natural ventilation in arid regions and especially in offices. Mixed-mode or hybrid systems were introduced as the alternative to natural ventilation that makes maximum natural ventilation usage with supplementary use of mechanical systems in extreme weather conditions (Ezzelding et al. 2013). These systems utilize windows and HVAC systems control to harness natural ventilation, minimize energy use, and provide occupants comfort. As per Schulze et al. "Open plan" offices are preferred to be controlled automatically rather than manually for better comfort (Schulze et al. 2013, Deuble et al. 2012). The hybrid system alternates between systems in an automatic manner as per the comfort temperatures allowed for natural ventilation (Lomas et al. 2009). This system has several advantages of which: (i) extend the applicability of natural ventilation to a longer period of the year due to the control of windows opening (Alves et al. 2015). (ii) The embedded natural ventilation part of the system results in human adaptation to a wider range of outdoor conditions (Alves et al. 2015, Wang et al. 2015, and Humphreys et al. 1998). Research conducted on this system showed interesting results and proved its reliability (Alves et al. 2015, Schulze et al. 2013, Tuohy et al. 2007, Rijal et al. 2008, Inkarojrit 2004). However these studies have been mostly concerned with application in temperate climates and countries of Europe and limited assessments were conducted for the area of the Middle East (Ezzeldin et al. 2013). Moreover, the conducted studies on mixed mode cooling in the Middle East did neither consider the performance of the system in the future facing climate warming nor the cost of installing such systems.

In this study, a hybrid system (Mixed Mode system) is assessed for applicability in the area of Lebanon, Middle East. Lebanon was chosen being a country with a moderate climate which allows the use of such systems. The objective of this study is to perform a quantitative assessment of the energy saving potential of hybrid systems in office buildings in Lebanon under present and future climates. The approach followed consists of: (i) performing dynamic simulations under present and future climatic conditions for a typical office building in Lebanon (ii) deducing its energy consumption patterns over the years (iv) performing a life cycle cost analysis of the system. The raised concern regarding the future and the lifecycle cost is due to the fact that the Middle East is prone to significant “cross roads” air pollution leading to serious climate warming effects (Lelieveld et al. 2002). This affects the energy saving potential of the proposed system in the future which brings the need to quantify the climate warming effect on the system. Dynamic simulations are performed on a typical office building in Beirut Lebanon under the hybrid mode approach in the present and the future using IES-VE.

CHAPTER II

DEFINING WEATHER DATA AND CONTROL STRATEGIES

In this study, the potential of hybrid system in providing thermal comfort for workers is assessed and its energy consumption is simulated. In order to conduct the simulations, dynamic simulation software is needed with software capability of performing complex thermal modeling of natural ventilation and hybrid systems. IES-VE is used, being a commercially available dynamic simulation software that was suggested by many researchers (Pollock et al. 2009; Annan et al. 2014; Azhar et al. 2009) for similar studies.

A set of design parameters are taken as inputs into IES-VE software, these parameters are pivotal to the building performance. The parameters include: the present and future weather files of the country, the natural ventilation scheme, geometry, building orientation, construction material, windows specifications, occupancy density, equipment heat dissipation, schedules for occupancy and equipment and the designs of the heating and cooling systems. Also, a detailed control algorithm for the windows and the Air Conditioning (AC) system is needed to operate the hybrid system. The function of this control is to provide occupants comfort and save energy by simple alternation between the windows operation and the AC system's operation.

A. Lebanon current climate data and weather file

Located on the eastern side of the Mediterranean (latitude 33º 49N; Longitude 35º 29E) with a 220Km long coast line (Haddad et al. 2014), Lebanon has a climate characterized by hot summers and mild rainy winters. Beirut is the capital of the country, its financial center and the countries' largest urban conglomerate. This city is prone to a hot microclimate caused by the Urban Heat Island Effect (UHIE) (Ministry of public works & transport 2005). Lebanon undergoes temperature ranges of 5°C to 38°C over the seasons. Moreover, humidity levels in the area vary between 55% and 70% with highest humidity level witnessed in Beirut city. Solar radiation in the country is mostly uniform in the upper atmosphere but depends on the cloud cover of the cities at the people’s level (Ministry of public works & transport 2005).

To be able to assess Mixed Mode ventilation in Lebanon, the weather file of the country is one major input of IES-VE. A weather file is an hourly weather data file readable by the software containing weather characteristics of the country. As no particular year can have a perfect description of the actual country’s climate characteristics described above, Typical Meteorological Years (TMY) were developed to describe accurately the weather. A TMY weather file is generally a combination of weather parameters derived from previously measured weather data (over a period of 10 to 30 years) of which typical descriptive months were combined. These months have weather characteristics that are the most commonly encountered over the years and they are assembled using the Finkelstein-Schafer method (Jentsch et al. 2008). In our study, the current weather file used for the simulation represents the Typical Meteorological Year (TMY3) weather file for Lebanon for the TMY3 years (1991-2005). This weather file is collected in this study using the MeteoNorm software; it is a weather data generation software used by many scholars in the collection of weather files (Radhi 2009, Ineichen 2006).

B. Future weather data generation

Future Lebanon hourly weather data are needed for the future simulations. These weather data are estimated for the 2050’s using the IPCC HADCM3 (Hadely Center Coupled Climate Model). HadCM3 makes use of the CO2 emission scenario of a country to deduce the climate change pattern it will undergo. The CO2 emission scenario assumed for Lebanon is A2 which describes: (i) a country with high population growth where the local identities are not much changed, (ii) a more regionally than locally oriented economic development, (iii) a slow technological change. This scenario is the closets description of this country’s development compared to the other emission scenarios suggested by the IPCC. More description of the scenarios and of the HadCM3 model can be found on the IPCC official website (http://www.ipcc-data.org/sres/hadcm3_download.html). HadCM3 provides the monthly mean bulb temperatures Δt_{mwb}, diurnal temperature $\Delta T_{\max_m} - \Delta T_{\min_m}$, relative humidity Δr_m and monthly percentage mean change in solar irradiance $\Delta I_{h,m}$) over certain grid points on the earth and these grid points can be interpolated to get the exact target location (Johns 2003).

The morphing method developed by Belcher et al. 2005 consists of using previous climate observations (TMY datasets), to downscale HadCM3 future monthly projections into future hourly weather files (Belcher et al. 2005). For this study, a morphing tool "Climate change world weather generator" was used to produce the future 2050's weather files using the HadCM3 parameters interpolated onto the country's grid points and using the TMY datasets of the country: $\langle dbt_{0\max} \rangle_m$, $\langle dbt_{0\min} \rangle_m$; t_{0_m}; r_0; $I_{h,0}$. This morphing tool proved reliable in previous climate projection studies (Holmes et al. 2011, Costa 2014, Peng et al. 2013, Yi et al. 2014) and bases its calculation on the following equations:

The future hourly dry bulb and dew point temperature in the morphing method are given as follows (Wang et al. 2014):

$$t = t_0 + \Delta t_m + a_m \left(t_0 - \langle t_{0_m} \rangle \right) \tag{1}$$

Where t_0 is the current hourly (TMY) weather data, Δt_m is the monthly mean change obtained from HADCM3, a_m the temperature increase factor and t_{0_m} the monthly mean of the current weather data. The temperature increase factor mentioned above (a_m) is found as follows (Wang et al. 2014):

$$a_m = \frac{\Delta T_{\max_m} - \Delta T_{\min_m}}{\langle dbt_{0\max} \rangle_m - \langle dbt_{0\min} \rangle_m} \tag{2}$$

Where $\Delta T_{\max_m}$ and $\Delta T_{\min_m}$ are the monthly mean changes in diurnal temperature in the future, which are obtained from the HADCM3 model, and $\langle dbt_{0\max} \rangle_m$ and $\langle dbt_{0\min} \rangle_m$ are the monthly mean changes in diurnal temperature under current weather conditions.

For relative humidity and wind speed (being expressed as percentage changes in HADCM3) the following equation from Wang et al. 2014 applies

$$r = \left(1 + \frac{\Delta r_m}{100}\right) r_0 \tag{3}$$

Where r is the future wind speed or relative humidity, Δr_m the monthly mean change (in percentage) obtained from the HADCM3 data, and r_0 the current weather data.

For the solar irradiance on horizontal surface the calculation is as follows (Wang et al. 2014):

$$I_h = \left(\frac{1 + \Delta I_{h,m}}{\langle I_{h,0} \rangle_m} \right) I_{h,0} \tag{4}$$

Where I_h is the future hourly solar irradiance, $\Delta I_{h,m}$ the monthly mean change in solar irradiance, and $I_{h,0}$ the current hourly solar irradiance.

The current Typical Meteorological year (TMY) weather file can be transformed to future hourly weather file based on the HADCM3 data and Eq. (1)-(4) stated above.

C. Developing windows and HVAC control algorithm

The target of windows and HVAC system control algorithm in hybrid ventilation buildings is to provide occupants comfort and fresh air. To define occupants comfort in non-AC buildings, the ASHRAE 55 adaptive comfort model (Brager et al. 2001) was developed. This model defines a comfort range established based on a comprehensive database of survey locations that includes the Middle East (Ezzeldin et al. 2013). However, this comfort model only applies to naturally ventilated buildings and recommends that hybrid buildings get evaluated under Fanger's heat balance approach for more restrictive results (Brager et al. 2001). One reason behind this restriction might be that Mixed Mode buildings were not subject to sufficient studies while setting this standard (De Dear et al. 2002). In contrast, subsequent studies including studies in the Middle East have recommended the application of adaptive models in Mixed Mode buildings rather than Fanger's model (Ezzeldin et al. 2013, Lomas et al. 2009, Aggerholm 2002, Ezzeldin et al. 2009, and Ezzeldin et al. 2008). As a result of the above, the adaptive approach is applied in evaluating the performance of the mixed-mode system and in setting the control parameters of this study. The ASHRAE 55 adaptive comfort model suggests temperature limits upon which occupants are supposed to be 80% comfortable under natural ventilation (Brager et al. 2001). The 80% acceptability is adopted in this study and according to it, equations (1) and (2) for natural ventilation cooling and heating set-point temperatures are set (Alves et al. 2015, Wang et al. 2015)

$$T_{HL} = T_{out} \times 0.31 + 21.3 \tag{1}$$

$$T_{LL} = T_{out} \times 0.31 + 14.3 \tag{2}$$

Where T_{HL} is the upper 80% acceptability limit describing the highest set-point for natural ventilation in °C. T_{LL} represents the lower 80% acceptability limit describing the lowest set-point temperature for natural ventilation in °C, and T_{out} represents the mean outdoor temperature in °C.

Several hybrid ventilation control strategies were developed as per the humans comfort expectations for hybrid ventilated buildings (Ezzeldin et al. 2013, schulze at al 2013, Wang et al.

2015, Olesen et al. 2004). In this study a window control algorithm is described for optimum use of natural ventilation and thermal comfort.

The control algorithm operation used in this study is similar to the algorithm followed previously by Wang et al. 2015 and is illustrated in figure 1 (summer operation of the algorithm) and figure 2 (winter operation of the algorithm). Note that a proportional bandwidth of 2°C is used to linearly open or close windows each time divergence of indoor temperature from the natural ventilation set-points is detected. During the working hours, the algorithm applies with 24°C cooling set point (T_{AC}) and 21°C heating set point (T_{he}). As per Olesen et al. 2004, 20% people dissatisfaction is allowed in buildings operating under Mixed Mode systems (in the AC settings) this fact is used in our system to avoid discomfort due to sudden temperature variation. In our hybrid system, the fresh air flowrate provided is delivered by a supply fan (on as long as the mechanical system is on). The same control algorithm applies to non-working hours, but during these operations when windows are closed and the indoor temperature is above 26°C the AC will operate at 26°C set point to protect electrical equipment from overheating.

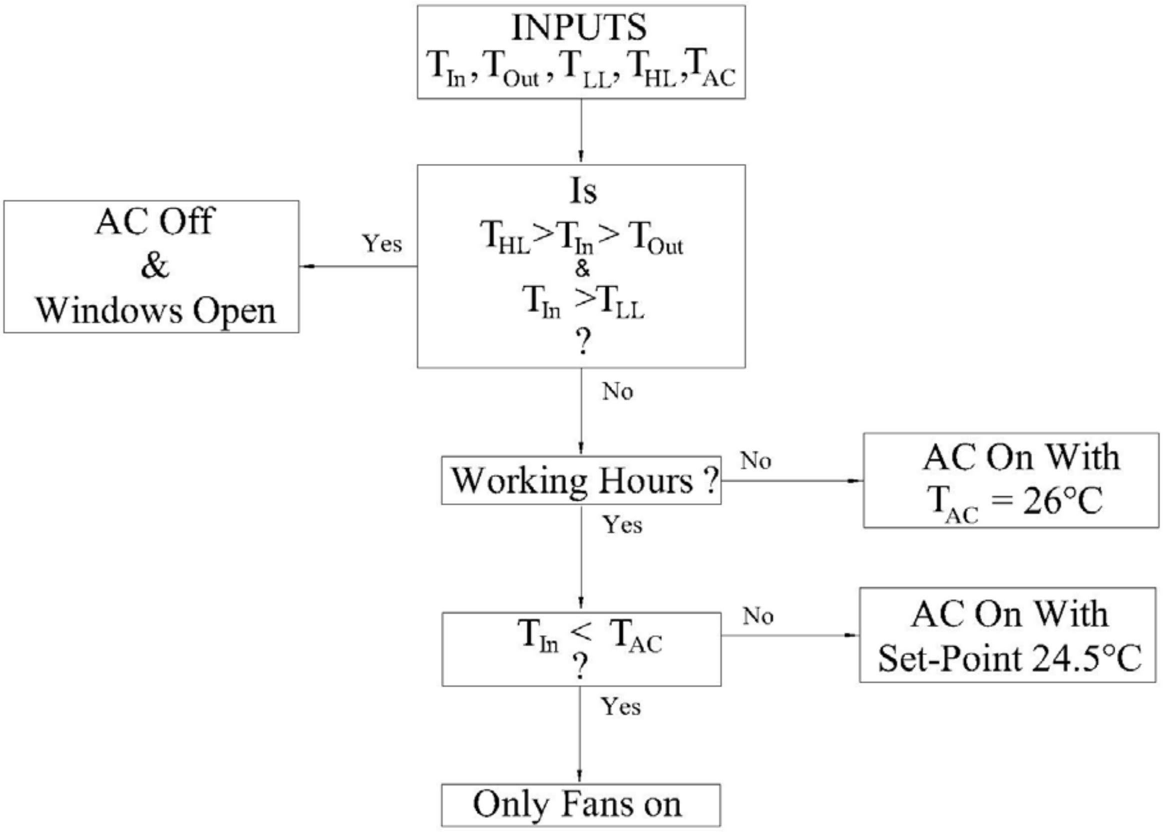

Figure 1: Summer operation control algorithm.

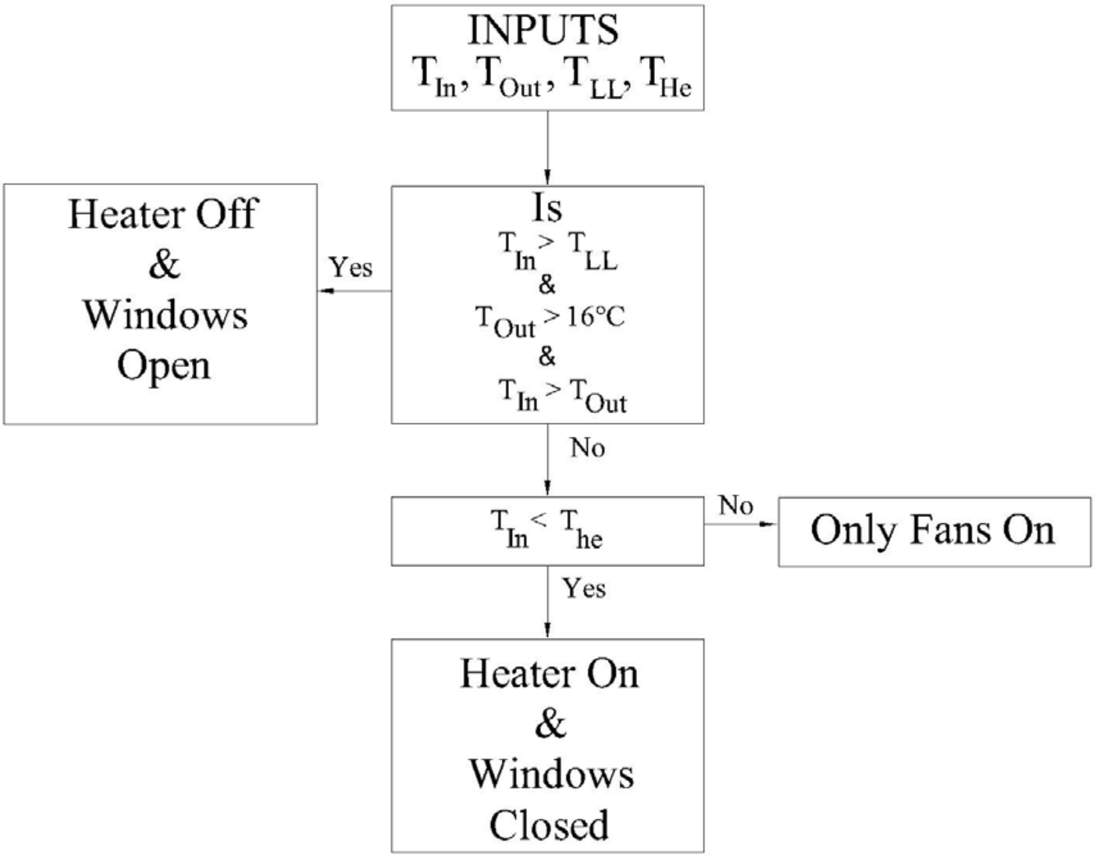

Figure 2: Winter operation control algorithm.

CHAPTER III

CASE STUDY: PROTOTYPICAL OFFICE BUILDING DESCRIPTION (BASE CASE)

A typical open plan (large open space) office was chosen for this study for the purpose of establishing base case energy consumption and assessing Mixed Mode ventilation. Being open plan where manual operation of windows is difficult, the office under study serves as a good test case for controlled hybrid ventilation principle. This office was built according to the typical building features used in the country. It is located on the fifth floor of a 25 years old building in the capital of Lebanon, Beirut. The office is distanced by 60m from the surrounding buildings in North-East, and by 6m from the surrounding building in the South-West. Described below are the features of the office (figure 3).

Table 1: Typical office construction material and corresponding U-Values

Construction Element	**Construction Materials (in to out)**	**U-Value (W/m^2K)**
External Walls	Plaster-Concrete Block-Plaster	1.8
Roof	Wood Wool-Mineral Fibre-Aerated Concrete-Asphalt Mastic Roofing	0.3
Ground Floor	Carpet-Reinforced Concrete-Insulation-Reinforced Concrete	0.7
Windows	Single Glass With 0.8cm thickness	5.2

Building Features:

- Rectangular single Zone space at roof level with an area of 832 m2 and a height of 3.7m.
- SE to NW building axis.
- 60% glazing on the south-west façade and 11% on the north-east facade
- Glazed surfaces are closed all the time even though operable.

The largest area with the highest occupancy is the offices part containing 42 employees each having a desktop computer. The office operation follows a schedule of 8h per day FROM 8am till 5pm with one hour lunch break all over the year during the weekdays, lights and equipment follow people's schedule except for computer servers (Computer servers remain on continuously).The lighting heat dissipation is 5000W. HVAC system operation is a low level operation during out-of-hours. The office's construction materials and glass properties are summarized in table 1 as per the actual office construction which is similar to the common practice in the country. The AC system of the building is a direct expansion (DX) unit, operational all year long with AC set-point of 23°C in the summer during the working hours, 26°C during non-occupied hours operation, and 22°C for the winter during the working hours. In the winter, no heating or cooling is on during the out of hours.

The electricity consumption of the actual office was monitored on monthly basis in the year 2013and varied as per figure 4. As seen in figure 4, the electricity consumption is prevailing in the peak summer months of July and August with 13.58 MWh and 13.4 MWh. The electricity consumption (figure 4) is the lowest during the months of February and March with 7.2 MWh and 6.93 MWh per month respectively. This low consumption is due to the fact that those months are classified as moderate months where HVAC energy consumption is low and the electrical equipment energy consumption is constant. The electricity consumption in the winter is 9MWh in the months of Dec and Jan.

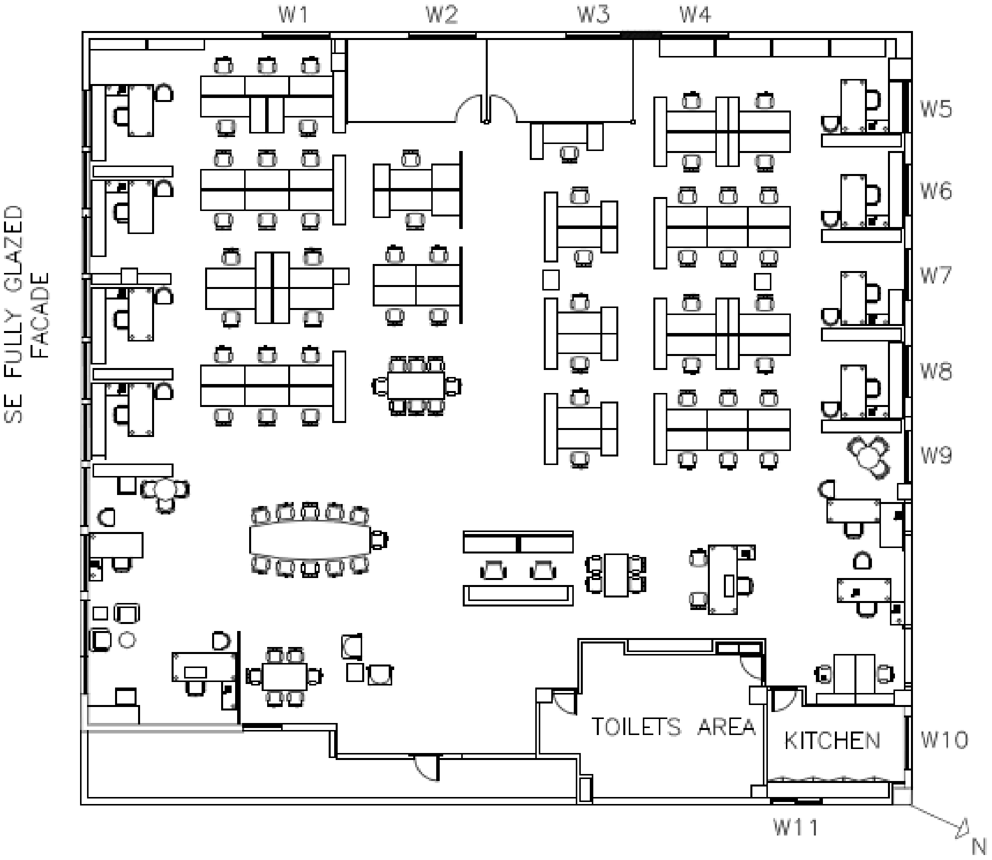

Figure 3: Typical open plan office layout in Beirut.

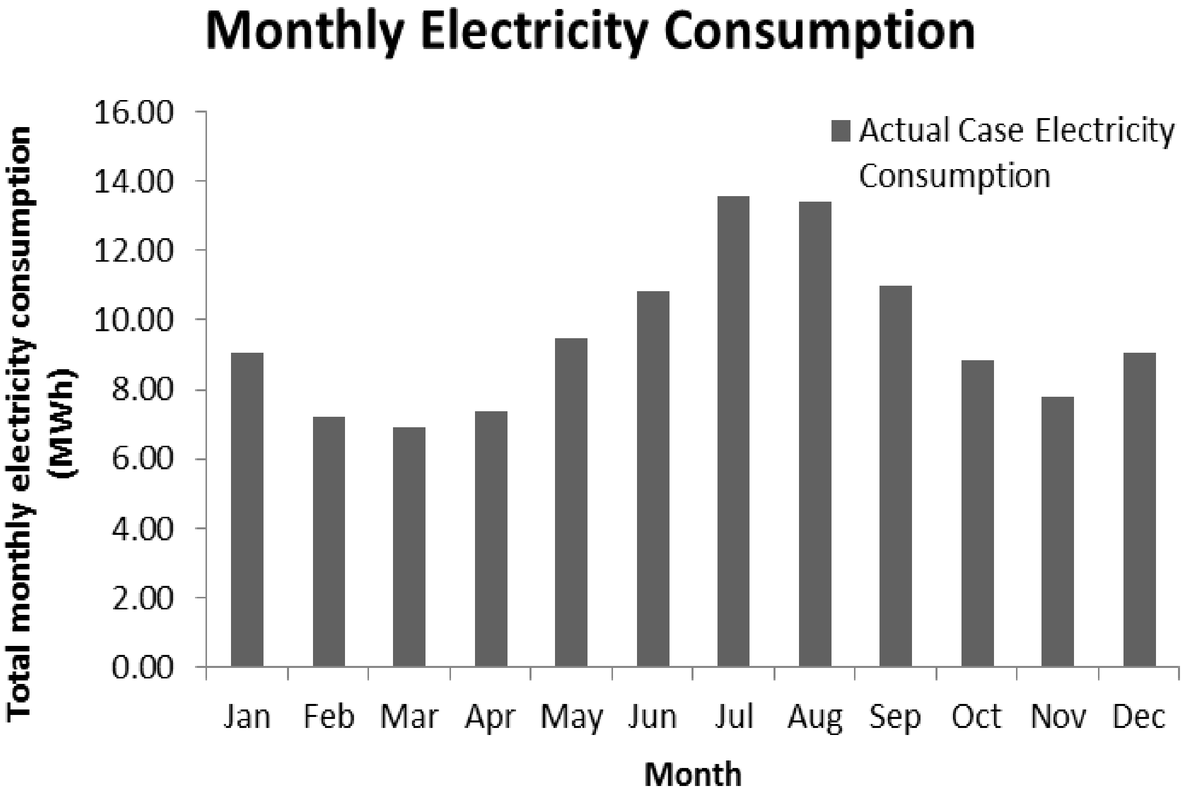

Figure 4: Measured total monthly electricity consumption for the year 2013.

CHAPTER IV

RESULTS

A. Validation of future weather data

The accuracy of the future weather data is a pivotal issue not to be ignored in the simulation process as the whole system's future assessment is based upon it. As the monthly dry-bulb temperature is one major input in energy simulations, the validation of this weather parameter is crucial for an accurate prediction of the system's energy performance. In order to validate the model, Wang et al.'s 2014 strategy was followed; two historical TMY data sets were used: TMY2 (1961–1990), and TMY3 (1991–2005). These data sets were first collected using the MeteoNorm software. The HADCM3 Data Distribution Center (DDC) was then used to get the monthly mean changes of dry bulb temperature for the years 1980's to 2020's. Then by applying the morphing method on the collected TMY2 historical data using the HADCM3 monthly means, the theoretical TMY3 data were generated. In order to validate the accuracy of the HADCM3 model, the actual TMY3 (1991–2005) information (collected from MeteoNorm) was compared against the theoretical TMY3 values from HADCM3 (using the morphing method). The steps of the validation process are shown in figure 5.

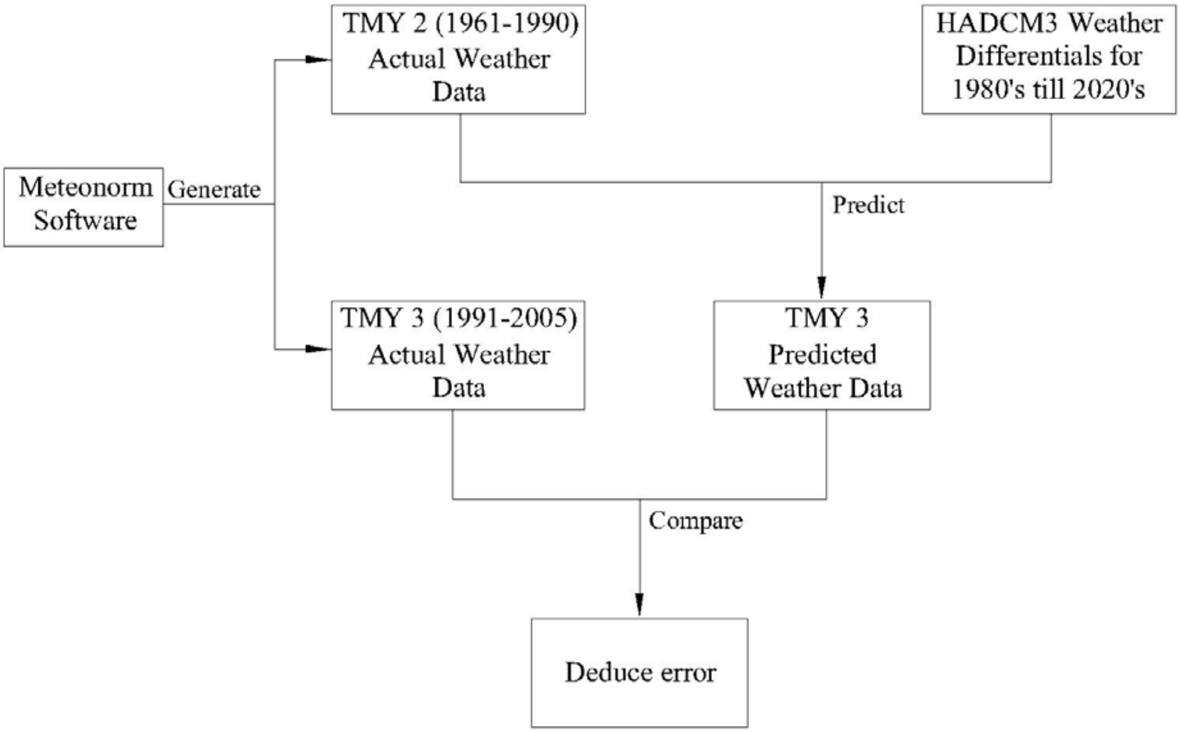

Figure 5: Flow chart followed during the validation of future weather data.

The average error between the actual and theoretical TMY3 weather data appear to be within the 10% error (largest differences noticed in the month May with an error of 9.2%. The closest predicted value to the actual data is in the month of December with an error of 1%). This 10% error is close to the error reported in the literature (Wang et al.’s 2014).

B. Lebanon future climate data

After validation of the model, the future weather file for the country was generated using the HADCM3 model. The future 2050’s climate for the country was remarkably characterized by a 2.1°C increase in average dry bulb temperature. The temperature increase is distributed as follows: 1.7°C Temperature increase in the winter, 2°C Temperature increase in the spring, 2.5°C Temperature increase in the summer and 2.1°C Temperature increase in the fall. Also an average relative humidity decrease of 1% is noticed by the year 2050. The decrease in relative humidity was expected due to the drying of the Mediterranean Middle East region discussed in the literature (Seager et al. 2007, Jentsch et al. 2010, Krichak et al. 2011).

C. Calibration of the IES model by measurement

The base case uses HVAC all year long; a simulation of the base case was performed using IES-VE. To conduct effective simulations with meaningful predictions of energy saving potential and measures, precise input data must be used (Agami 2006). To insure the accuracy of the simulation results , the simulation output must be tuned with measured data (Al-tamimi et al. 2011). For this reason, the measured monthly electricity consumption was used for the calibration of the IES model. This was performed by comparing the IES-VE simulation results with the electricity consumption measurements results. The steps of the calibration were performed based on the strategies summarized in Pan et al. 2006 study.

The office contains 49 computers and one laser printer, two desktop type scanners and one fax machine. The lighting heat dissipation in the office space is 5000W. An initial guess over the electrical equipment heat dissipation rate was based on the recommendation of ASHRAE Handbook 2013-Fundamentals chapter 18 data. According to ASHRAE fundamentals handbook chapter 18; each desktop computer consumes between 48W and 97 W depending on the computer specifications, a laser printer consumes 88W, a scanner consumes 16W, and a fax machines consumes 20W.

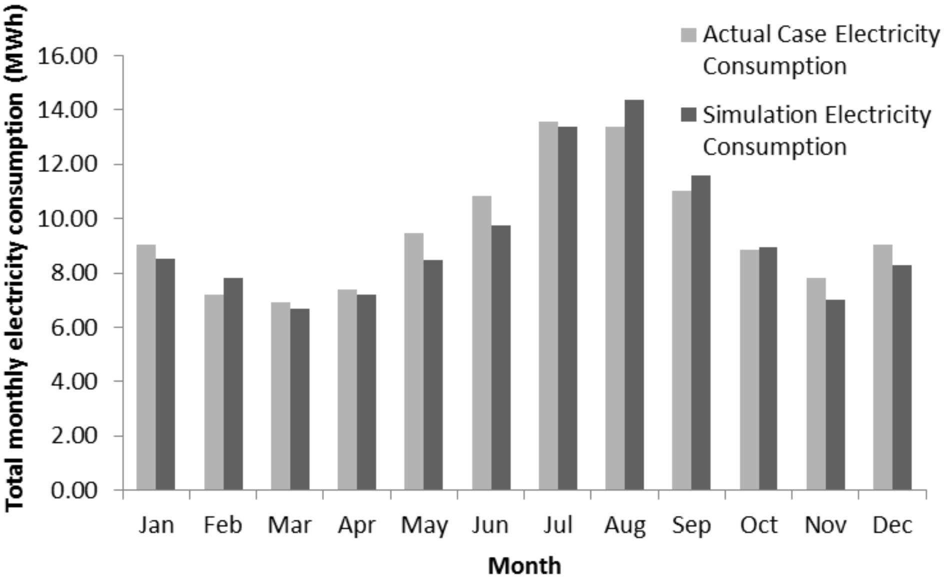

Figure 6: Actual vs simulation total monthly electricity consumption.

To get the best approximation between the measured and simulated data, adjustments in computers heat dissipation rates were implemented. Running the simulation using the 97W heat dissipation rate resulted in a high electricity consumption compared to the actual case. The rate was then decreased and tuned; the resultant heat dissipation rate of computers appeared to be 58.36W/Computer. This heat dissipation rate led to an electricity consumption 94% close to the actual consumption measured in the office with a maximum error of 10.4% occurring in the month of May. Figure 6 shows the actual electricity consumption against the simulated electricity consumption.

D. Mixed Mode operation:

In order to better understand the operation of the mixed mode system two typical TMY days are inspected, one summer day (August 13) and one winter day (January 2). Figure 7 and figure 8 illustrate the window opening and closing mechanism throughout these days in terms of ambient dry bulb temperature and indoor air temperature. These figures give a better picture about the hourly behavior of the system. Note that windows have an 84% effective openable area. As shown in figure 7, during the chosen summer day the outdoor temperatures vary between 24°C and 30°C. Inspecting the windows operation in figure 7 shows that a closure of windows is noticed when T_{out} becomes larger than T_{in} (at time 7:00 and 21:00). Once the window closes, the AC system turns on and the indoor temperature remains constant at T_{in} =24°C to T_{in}=24.5°C. As per the defined low operation of the AC system, during the non-working hours the AC set point becomes 26°C. This explains the increase in indoor temperature at time 17:00 till 20:00. At night the outdoor temperatures starts to drop and becomes close to T_{in} which leads to a linear opening of the windows (in the hours 20:00 till 23:00). The windows remain open as long as outdoor temperature is low and close to the indoor temperature (from 20:00 till 8:30). The indoor temperature remains less than THL in all cases.

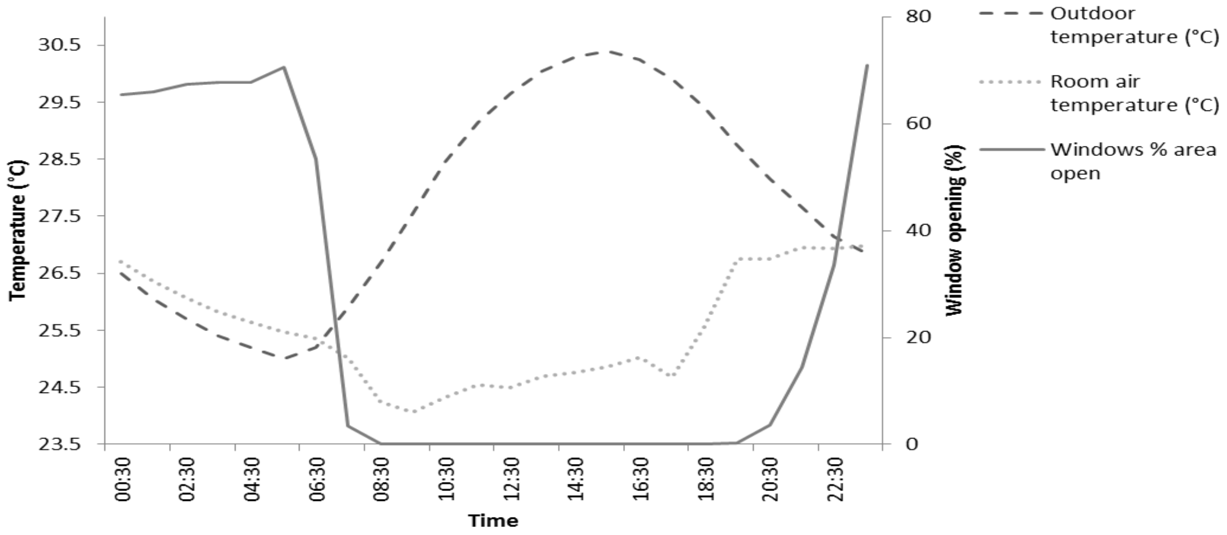

Figure 7: Temperature and window opening fraction for a regular summer (TMY) day of August

Figure 8 represents a sample of the simulation results on a TMY winter day (January 2). During this day the outdoor temperature varied between 15.5°C and 20.5°C and the windows open for three hours (14:30 till 17:30). As seen in figure 8 between time 14:30 and 17:30 the windows do not fully open, since each time the window starts to open linearly, the indoor temperature decreases and reaches the minimum level of TLL which triggers linear window closure. Note that in conformity with the winter window algorithm, the windows clearly start to open when the outdoor temperature becomes higher than 16°C and indoor temperature above T_{LL}. The temperature during the working hours is maintained within the 80% acceptability limit (between T_{LL} and T_{HL}) defined in the control algorithm.

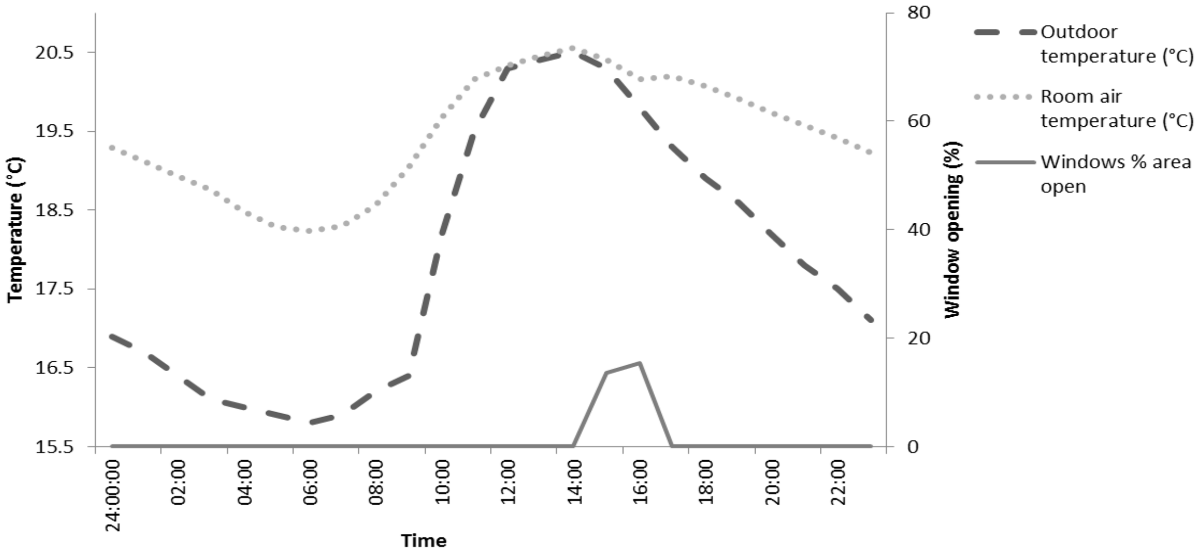

Figure 8: Temperature and window opening fraction for a regular winter (TMY) day of January.

CHAPTER V

DISCUSSION

Monthly HVAC energy consumption of the mixed mode system and the base case were simulated using IES-VE. In order to assess the energy saving potential of the mixed mode system, the base case energy consumption in the present is compared to that of mixed mode system. Figure 9 summarizes the monthly energy consumption of the Mixed Mode and the base case in the present TMY 3(1991-2005). As shown in figure 9 the mixed mode system has highest energy saving potential in November with 75% energy saving over the base case, and lowest energy saving potential in August with 9% energy savings. It can be noticed from figure 9 that during the fall and spring seasons (April, May, Octobe, November), important energy savings occurred with 60% savings against the base case. These energy savings are reasonable due to the fact that natural ventilation can be mostly used in the moderate months, this leads to fewer burdens on the mechanical system triggering less energy consumption. The winter season (December to March) energy saving potential is also high with 37% energy savings against the base case; this energy saving potential is achieved due to the 20% dissatisfaction allowed in the mixed mode system algorithm. The summer season (July to September) represents least energy saving potential with 24.5% savings against the base case. This small energy saving potential was noted due to the high outdoor temperature in the summer that minimizes the use of natural ventilation.

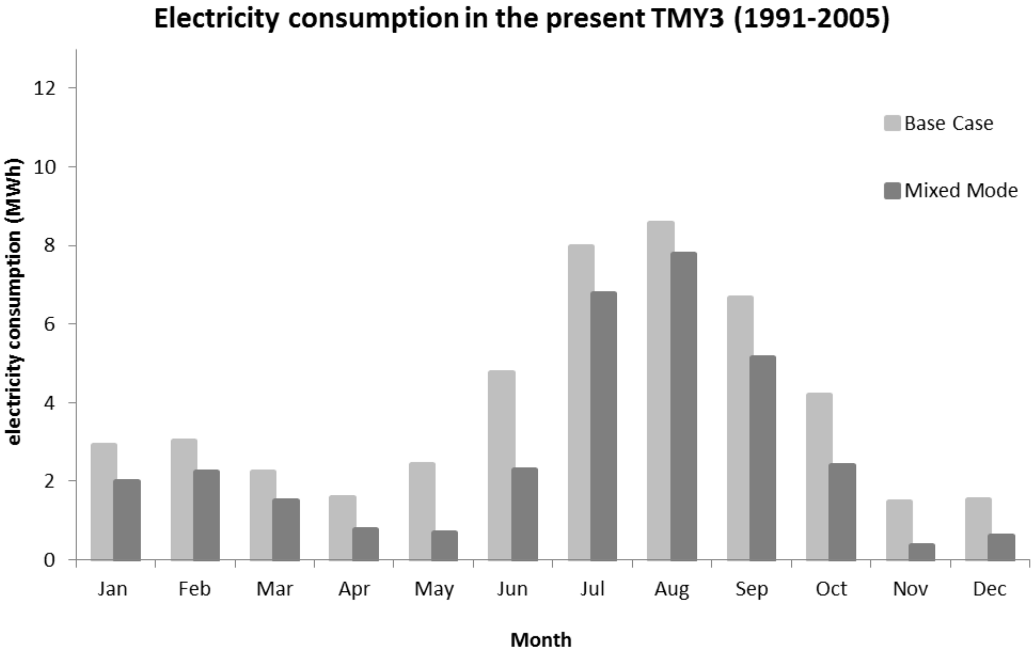

Figure 9: Base case and mixed mode system monthly electricity consumption in the present TMY3 (1991-2005).

After assessment of the monthly energy savings of the system, the total annual energy savings were assessed. The total annual energy consumption of the base case for the present TMY3 (1991-2005) is 47.5 MWh and became 32.7 MWh when the Mixed Mode system was introduced. This represents total annual 31% energy saving against the base case. A comparison to the literature is implemented to make sure the annual energy savings results are reasonable. A 35% reduction in the energy consumption of office buildings was obtained in Ezzeldin et al. 2013 study (the case where only Mixed Mode system was operational in the Middle East and North Africa (MENA) region) which is close to the 31% energy savings obtained in this study.

A comparison of the base case energy consumption between the present and the future was performed. Figure 10 summarizes the monthly energy consumption of the base case in the future (2040-2069). As shown in figures 9 and 10, a decrease in future energy consumption of the base case is noticed in the months of winter. This reduction is due to the increase in outdoor temperature that makes the weather more appealing and limits the need for heating. A rise in the future energy consumption of the base case was noticed for the rest of the seasons especially in the spring. During the spring season the office would need more energy to be cooled due to the increase in outdoor temperatures making the season more hot than moderate.

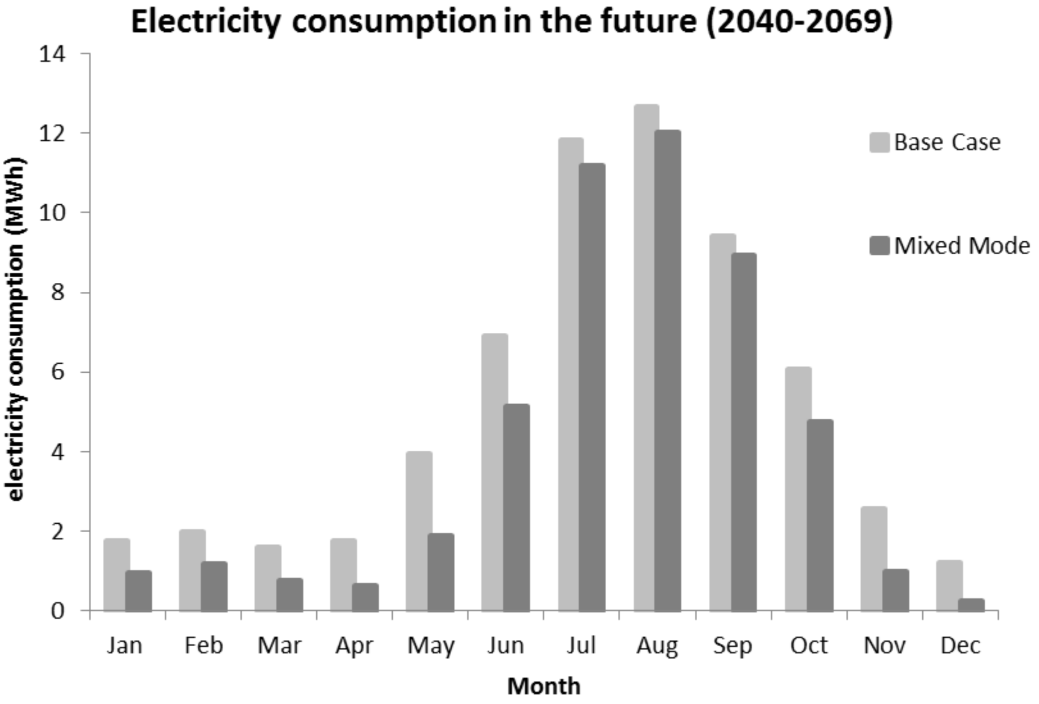

Figure 10: Base case and mixed mode system monthly electricity consumption in the future (2040-2069).

The future energy saving potential of the system was then assessed by comparing the future energy consumption of the base case to the future energy consumption of the mixed mode system (figure 10). As shown in figure 10 the month with the highest energy saving potential in the future is December with 78% energy savings against the base case, the month with the lowest energy saving potential is August with 4.8% energy savings. The future energy saving potential of the mixed mode system decreased compared to the present during the fall and spring seasons (with 50% energy savings in 2050’s instead of the 60% energy savings in the present). This decrease occurs because the outdoor temperatures are becoming more hot than moderate in the fall and spring. The energy savings in winter increased in the future (54% energy savings in the 2050’s instead of the 37% present energy savings) due to the more moderate outdoor temperatures in that season in 2050’s. The energy saving potential of the system decreased drastically in the summer with only 10% energy savings in the future instead of the 24.5% energy savings in the present.

After inspection of the monthly energy savings of the system, the total annual energy savings were assessed for the future (2040-2069). The total annual energy consumption of the base case becomes 61.6 MWh in the future, and when the mixed mode system is introduced the energy consumption decreases to 49.9 MWh. This represents 19% total annual energy savings against the base case.

CHAPTER VI

ECONOMIC ANALYSIS

As the Mixed Mode system was not used extensively in the Middle East, it is important to complete an economic feasibility study of this system to make sure about its advantage over the traditional mechanical system. A system is cost effective whenever its initial cost and running costs are less than the lifetime present value of its savings (Ghaddar et al. 2013). The lifetime present value depends on the discount rate.

A. Calculating the net present value of the system:

The net present value (NPV) of including the Mixed Mode system in the studied office building was estimated taking into consideration the effect of climate warming on the energy cost. This process was performed based on the projected changes in the HVAC energy consumption after including the Mixed Mode system in the present and the future. The cost of electricity in Lebanon is currently at 17.14 US cent per KWh subsidized by EDL with average tariff rate of 9.4 US cent per KWh (Ruble et al. 2011) with a 2% assumed increase of electricity cost at a yearly rate (Julha et al. 2015).

The net present value equation is as follows:

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \tag{5}$$

Where NPV is the net present value, C is the future energy consumption, N is the holding period and r is the discount rate of return (Reyk et al. 2008).

In long-term economic analysis the discount rate is an important factor and it declines with time especially if the future discount rates are uncertain and thus a 2% marginal discount rate shall be applied on NPV of projects that last for over 75 years (Julha et al. 2015). This discount rate is used in our study in calculating the NPV of the Mixed Mode system taking climate warming cost into account.

To calculate the running cost and net present value of the Mixed Mode system, first the energy consumption for the Mixed Mode building and the base case were computed for the years 1990’s 2020’s, 2050’s and 2080’s. The energy consumption is assumed to vary linearly through the future (Bianco et al. 2009). Note that the electricity consumption of the motors operating the windows is negligible compared to the total electricity consumption of the office and thus was not accounted for in the calculations. To find the net present value of a system, the annual energy consumption of that system is needed over the years. As the electricity consumption for the years (1990’s, 2020’s, 2050’s and 2080’s) can be calculated instead of annual electricity consumption, a linear regression analysis was performed over the resultant electricity consumption of the simulated years (1990’s, 2020’s, 2050’s and 2080’s) to find the electricity consumption of the intervening years. This method was adopted previously by Holmes et al. 2011. After finding the annual electricity consumption, the price of this electricity consumption was computed by multiplying the electricity consumption with its corresponding energy cost. The electricity cost is assumed to increase at a 2% inflation rate (Ghaddar et al. 2003). The results were then input into equation 5 with future cash flow being the annual electricity consumption, discount rate of 2%, and holding period of 75 years (2015 to 2090).

The initial cost of a Mixed Mode system control built from a normal cooling system is around 5000$ in the Lebanese market price and the cost is divided into sensors and transmitters cost, controllers cost, actuators and electric window openers cost. The mixed mode system is assumed to undergo replacement once every 20 years to last for the building lifecycle. The calculations of the net present value of the system resulted in a total of 22% savings over the 75 years of the Mixed Mode system compared to the base case with initial cost and discount rate taken into account. Finally the payback period of the mixed mode system was computed and appeared to be 3.8 years.

CHAPTER VII

CONCLUSION

By operating an office under its regular cooling system and typical construction practices, huge savings could be achieved by simple window operation strategies and simple alteration between natural ventilation and mechanical cooling. These strategies affect positively the energy efficiency and the occupant’s thermal comfort. Using the mixed mode approach the energy consumption of the office decreases by 31% in the present and by 21% in the future. The following opportunities were identified for future studies around the subject:

-Enhance the building envelope features for a better performance of the system in the present and the future.

-Perform CFD on the naturally ventilated space during peak natural ventilation day to provide detailed information about the indoor thermal environment and improve model prediction.

-Implement the Control strategies on a real existing building to assess whether the predictions align with the actual case.

BIBLIOGRAPHY

Agami Reddy, T. (2006). Literature review on calibration of building energy simulation programs: Uses, problems, procedures, uncertainty, and tools.ASHRAE transactions, 226-240.

Aggerholm, S. (2002). Hybrid ventilation and control strategies in the Annex 35 case studies. Danish Building and Urban Research, Denmark.

Al-Tamimi, N. A., & Fadzil, S. F. S. (2011). The potential of shading devices for temperature reduction in high-rise residential buildings in the tropics.Procedia Engineering, 21, 273-282.

Alves, C. A., Duarte, D. H., & Gonçalves, F. L. (2015). Residential buildings' thermal performance and comfort for the elderly under climate changes context in the city of São Paulo, Brazil. Energy and Buildings.

Annan, G., Ghaddar, N., & Ghali, K. (2014). Natural ventilation in Beirut residential buildings for extended comfort hours. International Journal of Sustainable Energy, 1-18.

Azhar, S., & Brown, J. (2009). BIM for sustainability analyses. International Journal of Construction Education and Research, 5(4), 276-292.

Belcher, S. E., Hacker, J. N., & Powell, D. S. (2005). Constructing design weather data for future climates. Building Services Engineering Research and Technology, 26(1), 49-61.

Brager, G. S., & de Dear, R. (2001). Climate, comfort, & natural ventilation: a new adaptive comfort standard for ASHRAE standard 55.

Bianco, V., Manca, O., & Nardini, S. (2009). Electricity consumption forecasting in Italy using linear regression models. Energy, 34(9), 1413-1421.

Cardinale, N., Micucci, M., & Ruggiero, F. (2003). Analysis of energy saving using natural ventilation in a traditional Italian building. Energy and buildings, 35(2), 153-159.

Costa, A. (2014). Effect of a global warming model on the energetic performance of a closed loop solar thermal energy system. Revista Ciência e Tecnologia, 17(31).

De Dear, R. J., & Brager, G. S. (2002). Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy and buildings, 34(6), 549-561.

De Reyck, B., Degraeve, Z., & Vandenborre, R. (2008). Project options valuation with net present value and decision tree analysis. European Journal of Operational Research, 184(1), 341-355.

Deuble, M. P., & de Dear, R. J. (2012). Mixed-mode buildings: A double standard in occupants' comfort expectations. Building and Environment, 54, 53-60.

Ezzeldin, S., Rees, S., & Cook, M. (2008). 589: Energy and Carbon Emission Savings due to Hybrid Ventilation of Office Buildings in Arid Climates.

Ezzeldin, S., Rees, S., & Cook, M. (2009, July). Performance of mixed-mode cooling strategies for office buildings in arid climates. In Proceedings of the 11th International IBPSA Conference, Glasgow, Scotland.

Ezzeldin, S., & Rees, S. J. (2013). The potential for office buildings with mixed-mode ventilation and low energy cooling systems in arid climates. Energy and Buildings, 65, 368-381.

Ghaddar, N., Ghali, K., & Najm, A. (2003). Use of desiccant dehumidification to improve energy utilization in air‐conditioning systems in Beirut.International Journal of Energy Research, 27(15), 1317-1338.

Griffiths, M., & Eftekhari, M. (2008). Control of CO 2 in a naturally ventilated classroom. Energy and Buildings, 40(4), 556-560.

Haddad, E. A., Farajalla, N., Camargo, M., Lopes, R. L., & Vieira, F. V. (2014). Climate change in Lebanon: Higher-order regional impacts from agriculture. REGION, 1(1), 9-24.

Holmes, S. H., & Reinhart, C. F. (2011). Climate change risks from a building owner's perspective: assessing future climate and energy price scenarios. In Building Simulation.

Humphreys, M. A., & Nicol, J. F. (1998). Understanding the adaptive approach to thermal comfort. ASHRAE transactions, 104, 991.

Ineichen, P. (2006). Comparison of eight clear sky broadband models against 16 independent data banks. Solar Energy, 80(4), 468-478.

Inkarojrit, V., & Paliaga, G. (2004, September). Indoor climatic influences on the operation of windows in a naturally ventilated building. In Proceedings of the 21st international conference on passive and low energy architecture (pp. 19-22).

Jentsch, M. F., Bahaj, A. S., & James, P. A. (2008). Climate change future proofing of buildings—Generation and assessment of building simulation weather files. Energy and Buildings, 40(12), 2148-2168.

Jentsch, M. F., James, P. A., & Bahaj, A. S. (2010). Climate Change adapted simulation weather data: implications for cities in hot, arid climates of the Middle East. In World Renewable Energy Congress XI, Abu Dhabi, UAE.

Ji, Y., Lomas, K. J., & Cook, M. J. (2009). Hybrid ventilation for low energy building design in south China. Building and Environment, 44(11), 2245-2255.

Johns, T. C., Gregory, J. M., Ingram, W. J., Johnson, C. E., Jones, A., Lowe, J. A., ... & Tett, S. F. B. (2003). Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios. Climate Dynamics, 20(6), 583-612.

Jylhä, K., Jokisalo, J., Ruosteenoja, K., Pilli-Sihvola, K., Kalamees, T., Seitola, T., ... & Drebs, A. (2015). Energy demand for the heating and cooling of residential houses in Finland in a changing climate. Energy and Buildings, 99, 104-116.

Krichak, S. O., Breitgand, J. S., Samuels, R., & Alpert, P. (2011). A double-resolution transient RCM climate change simulation experiment for near-coastal eastern zone of the Eastern Mediterranean region. Theoretical and Applied Climatology, 103(1-2), 167-195.

Lelieveld, J., Berresheim, H., Borrmann, S., Crutzen, P. J., Dentener, F. J., Fischer, H., ... & Korrmann, R. (2002). Global air pollution crossroads over the Mediterranean. Science, 298(5594), 794-799.

Olesen, B. W., & Brager, G. S. (2004). A better way to predict comfort: The new ASHRAE standard 55-2004. Center for the Built Environment.

Pan, Y., Huang, Z., Wu, G., & Chen, C. (2006). The application of building energy simulation and calibration in two high-rise commercial buildings in Shanghai. Proceedings of SimBuild, 2-4.

Peng, C., & Elwan, A. F. (2013, April). How hot can the university campus get in 2050?: environmental simulation of climate change scenarios at an urban neighborhood scale. In Proceedings of the Symposium on Simulation for Architecture & Urban Design (p. 5). Society for Computer Simulation International.

Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. Energy and buildings, 40(3), 394-398.

Pfafferott, J., Herkel, S., & Wambsganß, M. (2004). Design, monitoring and evaluation of a low energy office building with passive cooling by night ventilation. Energy and Buildings, 36(5), 455-465.

Pollock, M., Roderick, Y., McEwan, D., & Wheatley, C. (2009). Building simulation as an assisting tool in designing an energy efficient building: A case study. Integrated Environmental Solutions Limited, White Paper.

Radhi, H. (2009). A comparison of the accuracy of building energy analysis in Bahrain using data from different weather periods. Renewable Energy, 34(3), 869-875.

Republic of Lebanon, Ministry of Public works and transport (2005). Climatic zoning for buildings in Lebanon. United Nations Development Programe.

Rijal, H. B., Tuohy, P., Nicol, F., Humphreys, M. A., Samuel, A., & Clarke, J. (2008). Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings. Journal of Building Performance Simulation, 1(1), 17-30.

Ruble, I., & Nader, P. (2011). Transforming shortcomings into opportunities: Can market incentives solve Lebanon's energy crisis?. Energy Policy, 39(5), 2467-2474.

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., ... & Li, C. (2007). Model projections of an imminent transition to a more arid climate in southwestern North America. science, 316(5828), 1181-1184.

Schulze, T., & Eicker, U. (2013). Controlled natural ventilation for energy efficient buildings. Energy and Buildings, 56, 221-232.

Taleb, H. M. (2015). Natural ventilation as energy efficient solution for achieving low-energy houses in Dubai. Energy and Buildings, 99, 284-291.

Tuohy, P. G., Rijal, H. B., Humphreys, M. A., Nicol, J. F., Samuel, A., & Clarke, J. A. (2007). Comfort driven adaptive window opening behaviour and the influence of building design.

Ürge-Vorsatz, D., Eyre, N., Graham, P., Harvey, D., Hertwich, E., Jiang, Y., ... & Murakami, S. (2012). Chapter 10-Energy End-Use: Building. Global Energy Assessment-Toward a Sustainable Future, 649-760.

Wang, H., & Chen, Q. (2014). Impact of climate change heating and cooling energy use in buildings in the United States. Energy and Buildings, 82, 428-436.

Wang, L., & Greenberg, S. (2015). Window operation and impacts on building energy consumption. Energy and Buildings, 92, 313-321.

Wilkins, C. K. (2011). Plug load “BSigll Factors. Ashrae journal May 2011.

Williams, D., Elghali, L., Wheeler, R., & France, C. (2012). Climate change influence on building lifecycle greenhouse gas emissions: Case study of a UK mixed-use development. Energy and Buildings, 48, 112-126.

Yi, C. Y., & Peng, C. (2014). Microclimate change outdoor and indoor coupled simulation for passive building adaptation design. Procedia Computer Science, 32, 691-698.