
International Journal of Sustainable Energy

ISSN: 1478-6451 (Print) 1478-646X (Online) Journal homepage: http://www.tandfonline.com/loi/gsol20

# Natural ventilation in Beirut residential buildings for extended comfort hours

Ghina Annan, Nesreen Ghaddar & Kamel Ghali

**To cite this article:** Ghina Annan, Nesreen Ghaddar & Kamel Ghali (2016) Natural ventilation in Beirut residential buildings for extended comfort hours, International Journal of Sustainable Energy, 35:10, 996-1013, DOI: 10.1080/14786451.2014.972403

**To link to this article:** http://dx.doi.org/10.1080/14786451.2014.972403

Published online: 24 Oct 2014.

*International Journal of Sustainable Energy*, 2016
Vol. 35, No. 10, 996–1013, http://dx.doi.org/10.1080/14786451.2014.972403

# Natural ventilation in Beirut residential buildings for extended comfort hours

Ghina Annan, Nesreen Ghaddar* and Kamel Ghali

*Department of Mechanical Engineering, Faculty of Engineering and Architecture, American University of Beirut, P.O. Box 11-236, Riad El Solh, Beirut 1107 2020, Lebanon*

(*Received 1 August 2014; accepted 27 September 2014*)

This paper examines the effectiveness of natural ventilation in Beirut for the purpose of extending comfort periods within living and sleeping zones of the residential buildings. A field survey is conducted to estimate the common window opening and degree profiles. A base case model representing a typical residential apartment located in Beirut was then adopted in integrated environmental solutions (IES) software and calibrated by experimentation through monitoring simulated and measured data indoor. The calibrated IES model was used to evaluate typical wall layering and building local materials and their role in improving indoor comfort with natural ventilation. The simulation results showed that an optimal wall configuration of higher insulation and capacitance, comprised of a 5 cm layer of strawboard sandwiched between a 2 cm × 10 cm wall of masonry Hempcrete units, achieved the highest degree of thermal comfort and enhanced comfort in winter season when compared to the base case.

**Keywords:** natural ventilation effectiveness; local building material; thermal comfort in naturally ventilated spaces

## Nomenclature

| | |
|---|---|
| $C_p$ | specific heat (kJ/kg K) |
| *DX* | direct expansion |
| *h* | height above the ground |
| *Hrs* | number of hours |
| *HVAC* | heating ventilation and air conditioning |
| *IAQ* | indoor air quality |
| *P* | wind pressure in (Pa) |
| *RH* | relative humidity (%) |
| SHGC | solar heat gain coefficient |
| *T* | temperature (°C) |
| $T_{comf}$ | optimum comfort temperature for natural ventilation |
| $T_{a.out}$ | outdoor air temperature |
| *U*-value | overall heat transfer coefficient (W/(m$^2$ K) |
| *u* | weather file wind speed input at height 10 m |

*Corresponding author. Email: farah@aub.edu.lb

| | |
|---|---|
| $V$ | reference wind speed (m/s) |
| WWR | windows to wall ratio |

*Greek symbols*

| | |
|---|---|
| $\rho$ | air density (kg/m$^3$) |

## 1. Introduction

The primary energy demand for residential buildings is dominated by the electricity demand for lighting and heating ventilation and air conditioning (HVAC). Mathews et al. (2001) have shown that air conditioning is responsible for a substantial share of energy use (50%). With advancement of building materials and designs, natural convection has become one of the alternatives for reducing energy consumption.

In moderate climates, natural ventilation is an attractive method for reducing energy use while maintaining a comfortable and acceptable indoor air quality. It can be split into two types: wind-driven and buoyancy-driven ventilations, or it can be a mixture of both (Linden 1999; van Moeseke et al. 2005; Larsen 2006; Baker 2011). Furthermore, Eftekhari and Pinnock (1998) examined natural ventilation inside a lightweight test room, where the predicted mean vote for thermal comfort indicated that the values in the afternoon significantly improved with higher internal velocity. Also, Etheridge and Zhang (1998) indicated a strong synergy between porous insulation and wind energy, which could lead to significant reductions in energy consumption. Serghides and Georgakis (2012) proved that the building envelope of residential buildings has the most cost-effective and energy-efficient impact on the building thermal performance in Mediterranean climate, for which external insulation was derived as the most effective for the Mediterranean climate. In addition, Eftekhari (1998) studied the thermal comfort in a naturally ventilated test room in the UK. It was deduced that adding a 200 mm thick layer of concrete to the walls improved the thermal comfort over the summer by 40% (Eftekhari 1998).

Natural ventilation is mainly intended for countries with low winter temperatures and moderate summer temperatures. Germany initiated the use of night natural ventilation for the office building (Pfafferott, Herkel, and Wambsganß 2004). Brazil (Arent, Paula, and Ghisi 2011) and Bangkok (Tantasavasdi, Srebric, and Chen 2001) approve and encourage the use of natural ventilation in residential buildings. On the other hand, natural ventilation could hardly be applied in hot and humid climates, such as the countries of the Arabian Gulf region. However, several countries, such as Dubai, started designing new buildings that implement passive cooling approaches combined with proper ventilation, courtyards, wind-towers, shading devices, thermal massr, and insulation to reduce energy consumption (Haggag 2008). UAE, Qatar, Algeria, Pakistan, and Afghanistan have started to develop different cooling strategies to create a thermally comfortable environment (Abdurahiman 1988; Al-Shaali 2002; Haggag 2008; Network 2013). Generally, it was found that natural ventilation can save 10–30% of total energy consumption (Walker 2010). In Thailand, 20% of energy savings in a year was achieved when natural ventilation was used in the winter months (Tantasavasdi, Srebric, and Chen 2001).

In Lebanon, natural ventilation has not been studied or regulated by building designers. Majority of its constructions rely on HVAC systems to provide thermal comfort inside the apartments, for which 40–44% of its energy consumption is consumed by HVAC (Holness 2009). Residential buildings consume 65–73% of electrical energy production in Lebanon (Houri and Ibrahim-Korfali 2005) and 80% if combined with commercial buildings (Houri 2006). The interest in this work is in the coastal zone which extends about 230 km in length (CDR 2005). The coastal zone has a minimum temperature of 7–16°C, a maximum temperature of 24–32°C, and a RH of 60–80% (UNDP 2005a, 2005b). A dry bulb temperature of 32°C and a RH of 55–66% can be regarded as satisfying and comfortable if accompanied by an air velocity of about 0.5 m/s (Ghaddar, Ghali, and Chehaitly 2011). Recently, Yassine et al. (2014) examined envelop design features that can potentially reduce the energy consumed in attaining appropriate thermal comfort levels in typical residential buildings. They evaluated wall configurations using natural carbon neutral material such as hemp fibres or Hempcrete mixed with concrete (Awwad et al. 2010; Tran et al. 2010) and rendered the mechanical ventilation a feasible option for attainment of comfort for the largest number of hours per year in Beirut climate. Yassine et al. (2014) reported an optimal wall configuration comprised of a massive wall made of a 5 cm layer of straw sandwiched between 2 cm $\times$ 10 cm of Hempcrete in the living zone, in addition to 10 cm of Hempcrete in the bedroom zone. The optimal configuration combined with modulation of mechanical ventilation was shown to reduce the operational cost of the house by 26.9% and the discomfort hours by 37.8% compared to the base case of conventional air conditioning. It is of interest to examine if such a configuration when combined with a natural configuration would also increase the number of comfort hours.

The objective of this work is to investigate the feasibility of the use of natural ventilation techniques in Lebanon, and more specifically in the coastal area of Lebanon. The monthly comfort hours and their percentage of total occupied hours are studied when using natural ventilation combined with the use of natural materials in building envelop to enhance comfort hours.

## 2. Research methodology

Typical building envelope materials used in Lebanon's residential buildings as well as two-wall configurations using natural carbon neutral material are considered to assess their role in enhancing natural ventilation feasibility to provide comfort in the different occupant zones: the living and bedroom zones. A base case model representing a typical residential apartment Beirut will be adopted in integrated environmental solutions (IES) software. The IES model and inputs will be verified and calibrated by experimentation. A field survey is conducted through a questionnaire to estimate the common window opening and degree profiles practiced by occupants. This survey data are used in the calibrated IES model in parametric simulations year round to obtain the effectiveness of natural ventilation associated with different local envelop material and climates in Beirut.

### 2.1. *Simulation model*

The IES virtual environment (IES-VE) is used as the simulation tool for studying building operational energy consumption and for assessing the feasibility of natural ventilation (Ahmed and Wongpanyathaworn 2012). Macroflo IES module is used to model and simulate air flow through openings in the building envelope, and ApacheSim IES module is used to model the heat transfer processes occurring in and around the building based on first-principles mathematical modelling of heat transfer (Macroflo, MacroFlo Calculation Methods 2012).

IES takes several inputs illustrated in the diagram shown in Figure 1. The model is built by constructing the floors and adjacencies and assigning the construction material, orientation and dimensions. Then, the geometry and albedo of the surrounding are explicitly modelled to consider the solar shading effect and wind impact. Windows area treated as sharp-edged orifices with a fixed discharge coefficient. The windows are specified by both the window to wall ratio (WWR) and by the discharge coefficient of the window. The glass performance is imported through a number of properties, such as visible light transmittance, shading coefficient, and conductance ($U$-value). Also, the window opening and degree profiles are specified along with

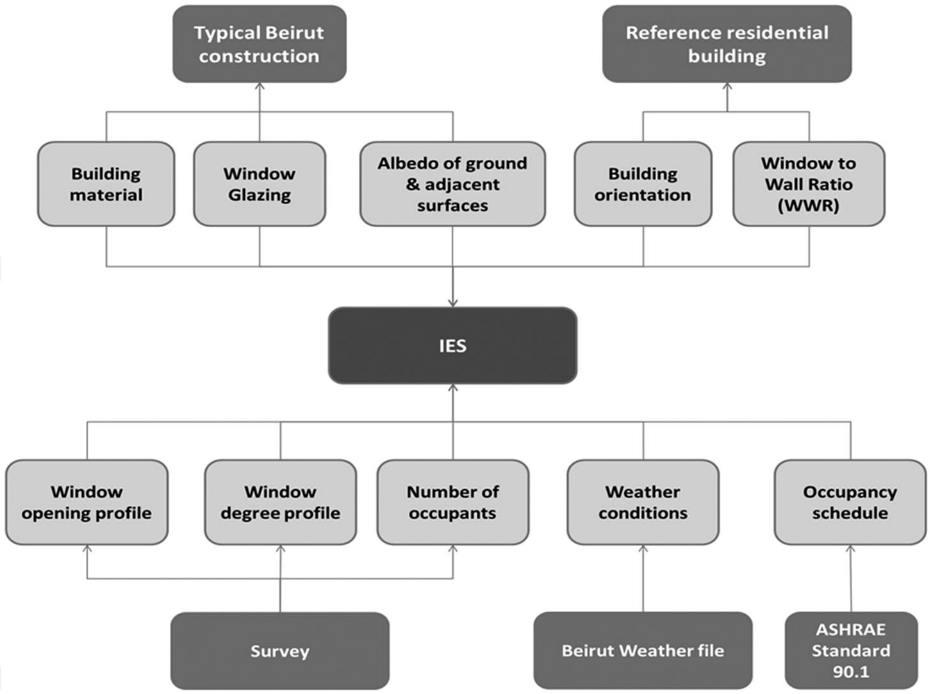


Figure 1. Diagram showing the inputs to IES.

the number of occupants, occupancy schedule, lighting/equipment, the internal gains, and the weather conditions. The window opening profile and window opening degree profile represent the period for which the occupants open their windows and the percentage of window openable area, respectively.

The simulation outputs of the IES model include the dry bulb indoor temperatures, indoor humidity ratio, $CO_2$ concentration, and air flow into the space. These parameters are used to evaluate the indoor thermal comfort for occupants due to natural ventilation. Results on thermal comforts are compared against the comfort limit set by ASHRAE Standard 55 (ASHRAE 2004). In order to study the thermal comfort, the simulated indoor temperature results are compared to the Adaptive Comfort Standard (ACS) for 80% acceptability limits (ASHRAE 2004) applicable for naturally ventilated buildings as shown in Figure 2. The Adaptive Comfort Model (ACM) predicts the occupants' thermal expectations in buildings that are naturally ventilated using the mean outdoor air temperature as an input variable (de Dear and Brager 2002; Taleghani, Tenpierik, and van den Dobbelsteen 2014) and is given by

$$T_{\text{upper}}(^\circ\text{C}) = 0.31 \times T_{\text{m.out}} + 21.3, \tag{1}$$

$$T_{\text{lower}}(^\circ\text{C}) = 0.31 \times T_{\text{m.out}} + 14.3. \tag{2}$$

Equations (2) and (3) represent the upper limit ($t_{\text{upper}}$) and lower limit ($T_{\text{lower}}$) of the comfort indoor temperature, with $T_{\text{m.out}}$ representing the prevailing mean outdoor air temperature, calculated as the arithmetic average of the mean daily minimum and mean daily maximum outdoor (dry bulb) temperatures. The simulated indoor temperature values that exceed the upper limit set by Equation (2) or are below the lower limit set by Equation (3) are considered uncomfortable. Accordingly, the hours of discomfort are calculated based on this comparison for every month and annually. The airflow, $CO_2$, and humidity inside the room are also compared against the ASHRAE standard limits indicated in Table 1 (ASHRAE 2004).

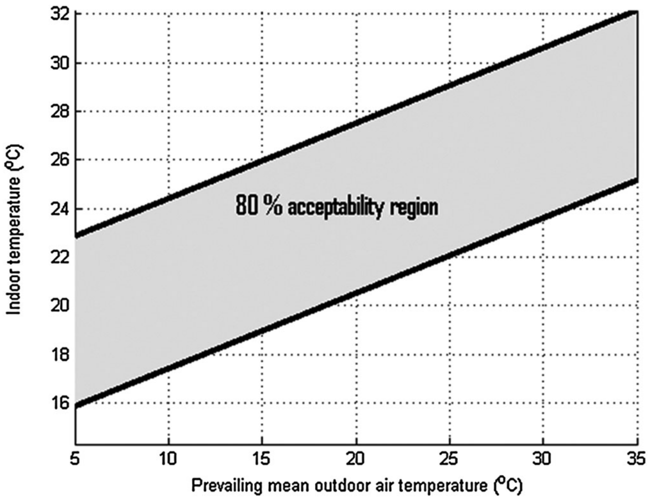


Figure 2. ASHRAE Standard 55, acceptability limits.

Table 1. ASHRAE 55 Allowable limits (ASHRAE 2004).

| Parameter | Minvalue | Maxvalue |
|---|---|---|
| Macroflo ext. Vent (l/s) | 0 | 10 |
| Room $CO_2$ concentration (ppm) | 400 | 1000 |
| Relative humidity (%) | 20 | 64 |

### 2.2. *Software calibration by experimentation*

The calibration of the IES-VE is performed by experimentally monitoring temperature and environmental conditions for a typical residential apartment during summer in Beirut and then comparing measured values with software predictions. The objective of the experiments is to calibrate the IES-EV software and to ensure predicting accurately the building performance for local conditions and materials in the presence of natural ventilation. An actual reference and typical residential building in Beirut was selected and is considered also the base case scenario for the subsequent simulations after the software calibration.

The reference building is a 10-storey residential building, located 24° from the north, with the dimensions of 10 m × 16 m × 30 m. Each floor of the building has an area of 160 m$^2$, distanced by 10 m from the surrounding buildings in south, east, and west, and by 5 m from the surrounding building in north. The typical apartment is modelled in IES as two zones, 100 m$^2$ living room zone and 60 m$^2$ bedroom zone. Cross ventilation between the two zones is absent due to the wall separation between them. The building geometry modelled in IES is shown in Figure 3, for which the apartment understudy is located at the fifth floor of the building.

The noise pollution effect due to window openings (Barclay 2012) is not accounted for in IES and hence is not addressed in our study. The building material for both zones consists of 25 cm concrete sandwiched between lightweight plaster ($C_p$ = 1000 J/Kg K) of 1 cm thickness, with an overall heat transfer coefficient $U$-value of 1.6 W/m$^2$ K, which is the typical one for Beirut constructions (OEA 2010). A uniform albedo is set to 0.3 for all surfaces of surrounding buildings with a ground albedo of 0.12 assumed for worn asphalt, typical to urban streets.

According to the Lebanese building law (Lebanese Construction Law 2005), every zone, living or bedroom, must have at least 1 window. The window area must not be smaller than 1/10 of the

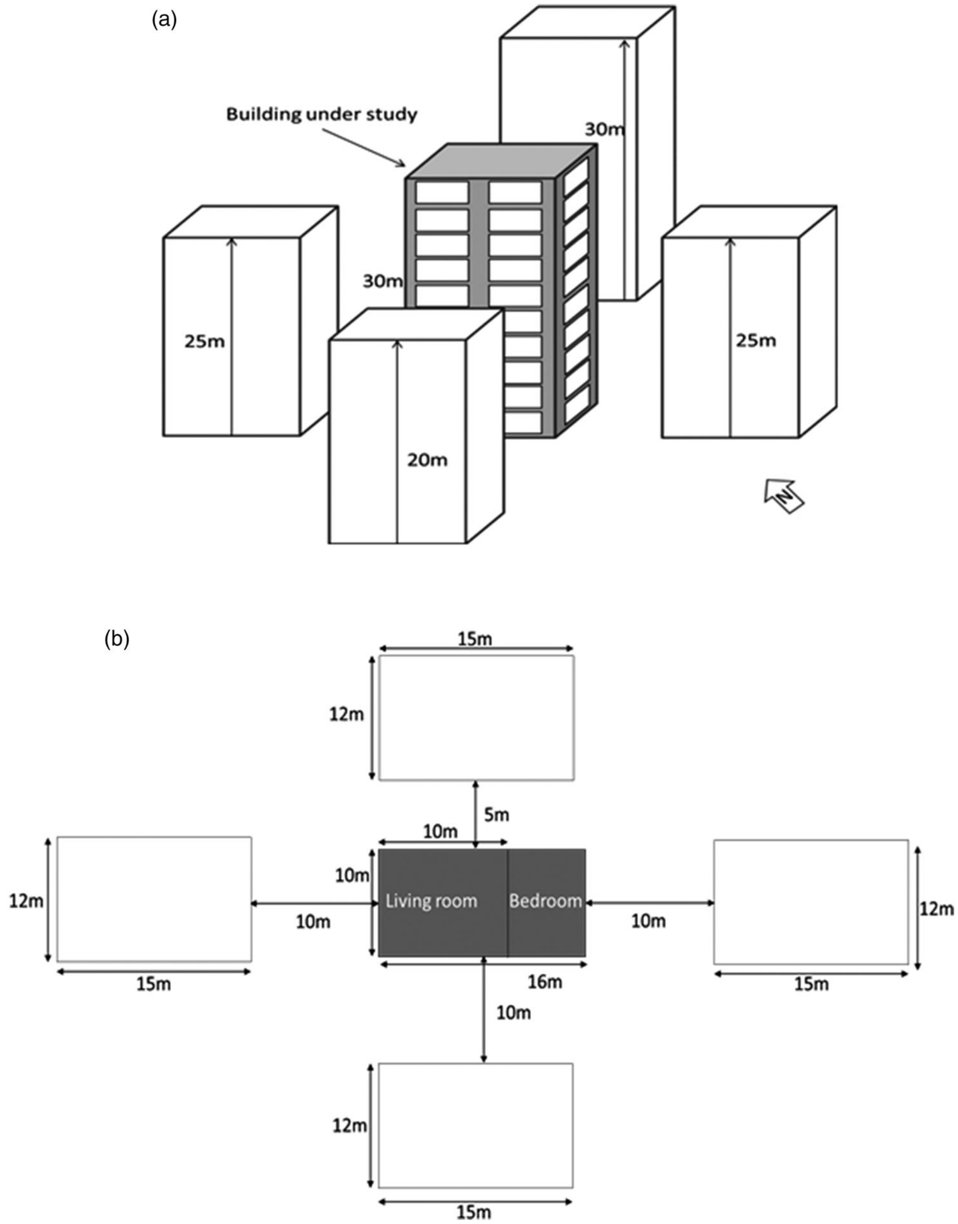


Figure 3. The building geometry of the similar building used for simulations: (a) facing north, (b) top view.

total area of the room (Lebanese Construction Law 2005). This is also considered in the base case scenario. Sliding windows are widely used in Beirut area and in the newly constructed building since it performs better in admitting natural ventilation (Gao and Lee 2010; Chilton et al. 2012). The windows are fitted in both zones as follows: 2 m × 6 m on west and south side of the living zone; 2 m × 5 m on south side; and 2 m × 6 m on east side of the bedroom. Internal doors within each zone, living and bedroom, are opened to allow air movement. The window glazing is composed of 6 mm clear float of conductivity of 1.06 W/m K, transmittance of 0.55, outside reflectance value of 0.4, inside reflectance of 0.05 and refractive index 1.526, a $U$-value of 5.69 W/m$^2$ K, and a solar heat gain coefficient (SHGC) of 0.6 (OEA 2010). The discharge coefficient for this type of windows is equal to 0.62. The WWR is taken to be 30%, similar to that of the residential building used in the measurements (OEA 2010). Based on ASHRAE 90.1 user manual, the lighting/equipment, occupancy daily profiles, and internal gains are added as indicated in Figure 4 and Table 2, respectively. The number of occupants is four (OEA 2010).

Finally, weather conditions are imported. The original weather is acquired from Global Meteorological Database (2013). However, in order to accurately study Beirut case, this weather file is updated using actual data from Beirut Air Base/Rafic Hariri International Airport for the duration of the monitoring in 2013. The airport is located 2 km from the experimental residential apartment.

In the base case scenario, the sliding windows, having an openable area of 50%, are open all day long to have a similar case to the residential apartment used in measurements where the windows have been kept open in the period of measurements. The base case scenario predicted temperature data were compared to the actual measured temperature data using OM-EL-USB-2 data logger sensing device placed inside the reference residential apartment. The data logger measured and stored temperature readings over a −35°C to + 80°C range, with a temperature $T$ maximum overall error of ± 2°C with a typical error of ± 1°C (OMEGA). The sensor is placed in the middle of the living zone, hanging down from the ceiling to a height of 2 m, with no obstruction to the sensing device. The measurements were done starting from the midnight of 22 July till the midnight of 29 July 2013. The data from the midnight of 25/26 July till midnight of 26/27 July were then taken to serve as a benchmark to validate the IES model.

After calibrating the IES model, the validated base case model is used to assess the effectiveness of natural ventilation throughout the year in each of the living and bedroom zones.

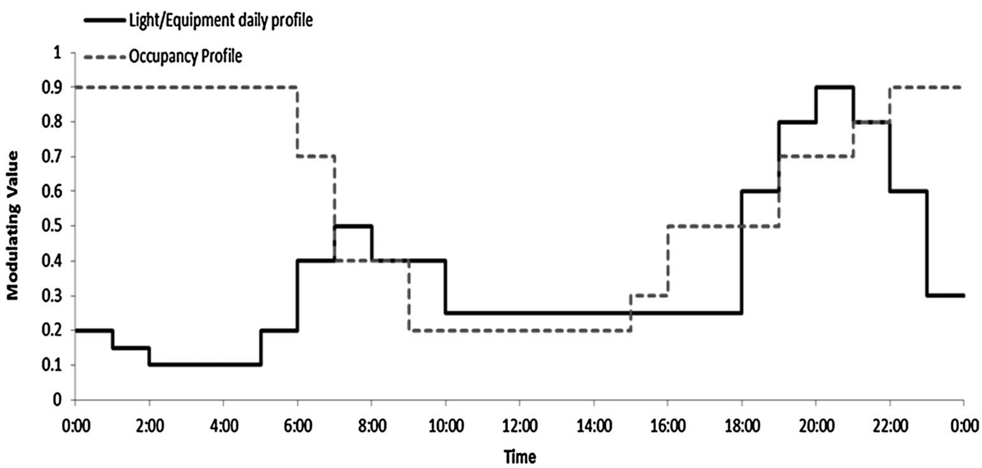


Figure 4. Lighting/equipment and occupancy daily profiles.

Table 2. Internal gains.

| | |
|---|---|
| Lighting and equipment | |
| Max. sensible gain | 10 W/m$^2$ |
| Max. power consumption | 10 W/m$^2$ |
| Occupancy | |
| Max. sensible gain | 50 W/person |
| Max. latent gain | 45 W/person |

## 3. Field survey of people comfort and associated window opening

### 3.1. *Field survey objective and outcomes*

A field survey is carried out among a population of occupants living in Beirut residential buildings in order to extract information about common occupants' adaptation in regulating the opening and closing of the windows in each season.

The questionnaire, shown in Appendix 1, consisted of 12 questions and requirements. Lebanon's employment rate is almost 90.7% (Byblos 2013); accordingly the working population is reliable in defining a clear trend of window opening profile. We selected 225 employed households living in Beirut to take the survey. The directory of the 225 participants' phone numbers and email addresses was provided by the Order of Engineers and Architects of Beirut. The survey was sent electronically with a clear guidance explaining to people some technical facts about natural ventilation, and asking the occupants to fill out the survey. The respondent rate was approximately 89% from 200 respondents. Survey participants were asked to specify the times they and their family members prefer to open the windows during the 24 h of a typical day in both bedroom and living room zones. Accordingly, this opening profile is assumed all year long but with variable opening degrees based on seasonal variation. The survey also provided the following valuable information:

(1) The average time of daily home occupancy and the number of occupants per apartment.
(2) The average apartment area, WWR and external windows.
(3) General satisfaction and free comments concerning natural ventilation.

The output values of the survey have been gathered, counted and tabulated using IBM SPSS Statistics software.

### 3.2. *Field survey results*

The field survey showed that 64% of the participants live in apartment block, with 71% among them having an apartment area ranging between 150 and 250 m$^2$, 63% living between the third and sixth floors, with 76% of the total participants having three to five occupants per apartment. The common WWR resulted to be 30% with 70% of participants. Most respondents indicated that during March, April and mid-May (spring season), natural ventilation is practiced and comfort is achieved. They assumed that natural ventilation is only effective in this period where the outside temperature is moderate compared to other seasons.

Studying the frequency at which occupants open the windows in both living room and bedroom, it is realised that most of the respondents have similar behaviour in regulating the opening and closing of the windows.

In the living zone, the percentage of respondents who open the windows during the period of 00:00 to 06:00 was only 5%. This frequency of respondents increases in the period between 06:00 and 17:00 reaching 40% of the total respondents. In the period 17:00–22:00, this frequency exceeded 50% of respondents and reaching 70% in the period 20:00–22:00. Then the frequency of respondents who open the windows decreased again at 22:00 to around 40% in the period 22:00–24:00.

A similar survey result analysis is done in the bedroom. The percentage of respondents who open the windows during the period 00:00–06:00 was around 40% of total respondents, still lower than half of the survey respondents. This frequency of respondents increased to around 60% in the period between 06:00 and 08:00, and then decreased again at 08:00 to under 50% and continued to decrease till reaching null frequencies in noon period. The frequency increased at

16:00 till reaching a frequency of 54% at 21:00. The frequency then continued to increase in the period 21:00 –24:00, reaching a frequency of around 70% between 22:00 and 24:00.

Literature studies have indicated that even though the window opening profile is related to environmental conditions such as indoor vs. outdoor temperature, it is also a function of personal factors: routine and habits of households, and arriving and leaving times (Herkel, Knapp, and Pfafferott 2008; Pfafferott and Herkel 2007; Xu, Fu, and Di 2009). Accordingly, a common window opening profile was adopted to reflect the behavior of occupants in opening and closing of the windows as in the following:

- In the living zone, window open from 17:00 to 22:00.
- In the bedroom, window open from 06:00 to 08:00 and from 21:00 to 24:00.

The survey also specified the estimated window opening degree profiles of occupants, which represent the degree to which the window can be opened depending on the season. As per the respondents, a minimal degree of 25% is preferred in rainy seasons and a maximal degree of 100% is preferred in hot seasons in which the temperature is too high and rain is of no concern. Both minimal and maximal degrees are reflected with degrees of 25% in fall and winter and 100% in spring and summer in IES.

## 4. Importing the weather file and validation of IES model

### 4.1. *Importing the weather file*

In order to replicate the original Beirut weather file, AUTODESK-Ecotect is used to import the data from an excel sheet that has the exact form of a weather file template. Actual Beirut weather data taken from Beirut Airport weather station have been added to the excel sheet, containing the temperature, relative humidity, wind speed, and wind direction, which mainly affect natural ventilation. The excel sheet for the whole year weather data is converted to EnergyPlus weather file format (.epw) using AUTODESK-Ecotect so that it can be read by IES.

### 4.2. *Calibration of IES model*

In order to calibrate IES results, the reference apartment used in measurements is modelled in IES. The sliding windows, with an openable area of 50%, are open all day long to have a case similar to the residential apartment used in measurements where the windows have been kept open in the period of measurements. The zone is susceptible to solar radiation throughout the day, which is also accounted in IES simulations. The simulation temperature results are then compared to the actual measured temperatures inside the reference apartment.

A comparison between the resulting simulated and measured temperatures inside the apartment showed a difference of 0.93°C between the two data starting the midnight of 25/26 July until the midnight of 26/27 July, taking into account the temperature error margin of the sensing device used and small variations between the model in IES and the actual reference building. To decrease this difference, a calibration of IES model was performed. Natural ventilation highly depends on wind flow and its interaction with the building envelope, on openings and on solar radiation. The wind flow is mainly dependent on the WWR, whereas the solar radiation reaching inside the apartment could be affected by the SHGC of the window used and the building material. The WWR is kept fixed, 30%. Any airflow into the apartment will be mainly from the open window with slight effect from any tiny cracks leaking air into the apartment.

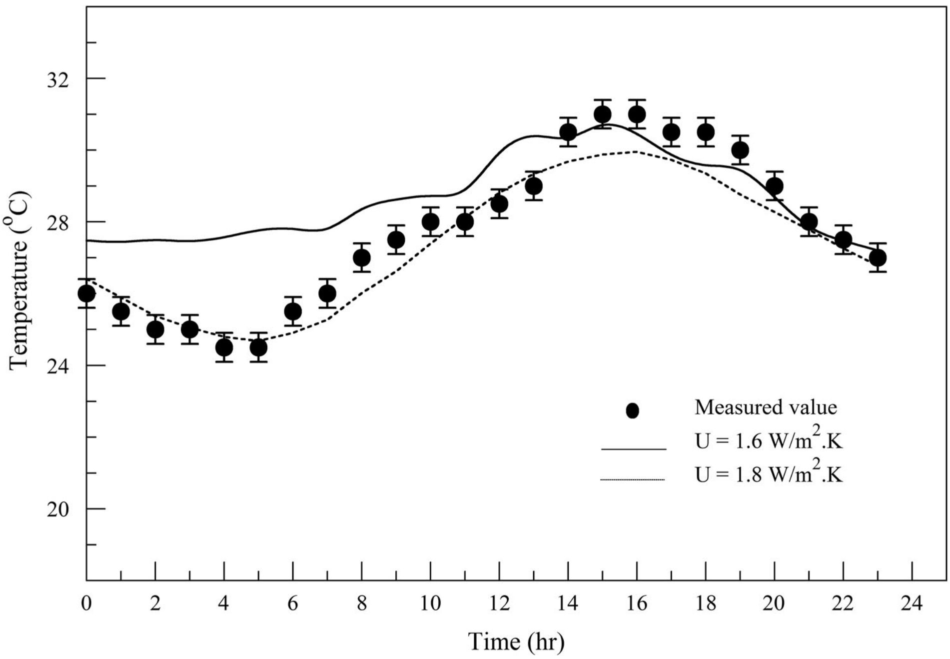


Figure 5. Measured indoor air temperature versus simulated temperature data (IES) over 24-hour period in July.

As a first step, SHGC was varied from 0.6 to 0.5 and then to 0.4, but no significant marginal difference is found through changing SHGC from 0.6 to 0.4 since the residential building is located in a congested area shaded by adjacent buildings.

In the second step, the building material $U$-value is altered. The existing calculation procedures for the $U$-values may often underestimate true heat losses for walls, in some cases by more than 30% (Doran and Kilbride 2000). A difference between calculated $U$-values and measured $U$-values highly exists, and it is correlated also with the construction type. Hence, the $U$-value of the building material is changed from 1.6 to 1.7 W/m$^2$ K and then to 1.8 W/m$^2$ K. The latter resulted in a decrease in temperature difference between measured and predicted values to 0.4°C (57% decrement) as shown in Figure 5. Hence, the calibrated base case building construction material is of a $U$-value equal to 1.8 W/m$^2$ K.

## 5. Results and discussion

The comfort due to natural ventilation is studied for the reference base case by simulation for the entire year. Typical local Beirut construction materials are used throughout the simulations along with the common window opening and degree profiles estimated from the survey. An average number of four occupants is used (OEA 2010). The calibrated base case model consisted of 25 cm concrete sandwiched between lightweight plaster ($C_p$ = 1000 J/kg K) of 1 cm thickness, with an overall calibrated heat transfer coefficient $U$-value of 1.8 W/m$^2$ K.

In calculating the number of comfort hours via natural ventilation in the parametric simulations, each zone is studied in a different time frame depending on the occupancy profile of a real-life situation. Accordingly, the bedroom's comfort is investigated during the time range 20:00–08:00 h, while the living zone's comfort is examined between 08:00 and 20:00 h. The percentage of comfort hours is calculated based on the number of comfort hours over the total

Table 3. Building construction material's properties.

| Case | Wall configuration | $U$-value W/($m^2$ K) |
|---|---|---|
| Base case | 10 cm Hempcrete sandwiched between light weight plaster | 1.6 |
| Case 1 | 10 cm of Hempcrete | 3.1 |
| Case 2 | 5 cm of straw sandwiched between 2 cm × 10 cm of Hempcrete | 0.7 |

number of occupied hours for each zone. The mid-day of each of the four seasons is first studied using the calibrated base case model.

Figure 6 illustrates the upper and lower temperature acceptability limits calculated for the base case using Equations (2) and (3), daily temperature variation of dry bulb temperature ($T_{out}$), and inside temperature in both living and bedroom for four different days: 5 February (mid-winter season), 5 May (mid-Spring season), 5 August (mid-summer season) and 5 November (mid-Fall season). Figure 6(a) demonstrates that indoor temperatures of both living and bedroom zones in winter are lower than the 80% acceptability limit of lower comfortable temperature defined in Equation (3), due to cold weather, thus discomfort is displayed. Figure 6(b) and (d) present the daily temperature variation in spring and fall respectively, demonstrating that indoor temperatures of both living and bedroom fall within the 80% acceptability region defined by $T_{upper}$ and $T_{lower}$ defined in Equations (2) and (3), with little discomfort observed in fall for around 5 h between 12:00 and 17:00 h. Accordingly, comfort is achieved and natural ventilation is reasonably a feasible option in spring. However, Figure 6(c) reveals that indoor temperatures of both living and bedroom in summer are higher than the 80% acceptability limit of high comfortable temperature defined in Equation (2), due to hot weather, thus discomfort is displayed.

We are interested in increasing the comfort hours during summer or winter by altering the envelop materials and evaluating its effect on extending comfort hours with natural ventilation. In summer, a lower insulation and a lower capacitance building material would perform better compared to the base case building material to prevent heat storage within the building walls. In cold days, walls with higher insulation perform better keeping warm air inside the space. Two-wall configurations using local low-embodied energy natural material in addition to the base case material were considered for both living zone and bedroom zone. These configurations are summarised in Table 3. Case 1 consisted of 10 cm of Hempcrete ($C_p$ = 1430 J/kg K). Case 2 (massive case) consisted of 5 cm of straw ($C_p$ = 2000 J/kg K) sandwiched between two layers of 10 cm Hempcrete. The thermal properties of straw were obtained from 'the green building bible' (Hall 2006) and the thermal properties of hemp were obtained from Elfordy et al. (2008).

The investigated configurations focused on selecting building materials that would result in a minimum number of discomfort hours (highest %comfort) throughout the whole year. The monthly percentage of comfort parameter (%comfort) in each zone is equal to the percentage of comfort hours in each month of the estimated total hours spent in each zone monthly.

Figure 7 shows the predicted monthly percentage of comfort in (a) bedroom and (b) living zones respectively for the base case, case 1, and case 2. Tables 4 and 5 summarise the predicted number of comfort hours for bedroom zone and living zone respectively. Further analysis of comfort percentage results based on seasonal climatic variation is presented in the next section.

### 5.1. *Base case comfort hours*

During July, August, and September, representing the summer season, the base case displays low comfort percentages of 22.05%, 18.82%, and 64.44% respectively in the living zone and higher comfort percentages of 35.71%, 38.67%, and 87.50% respectively in the bedroom zone.

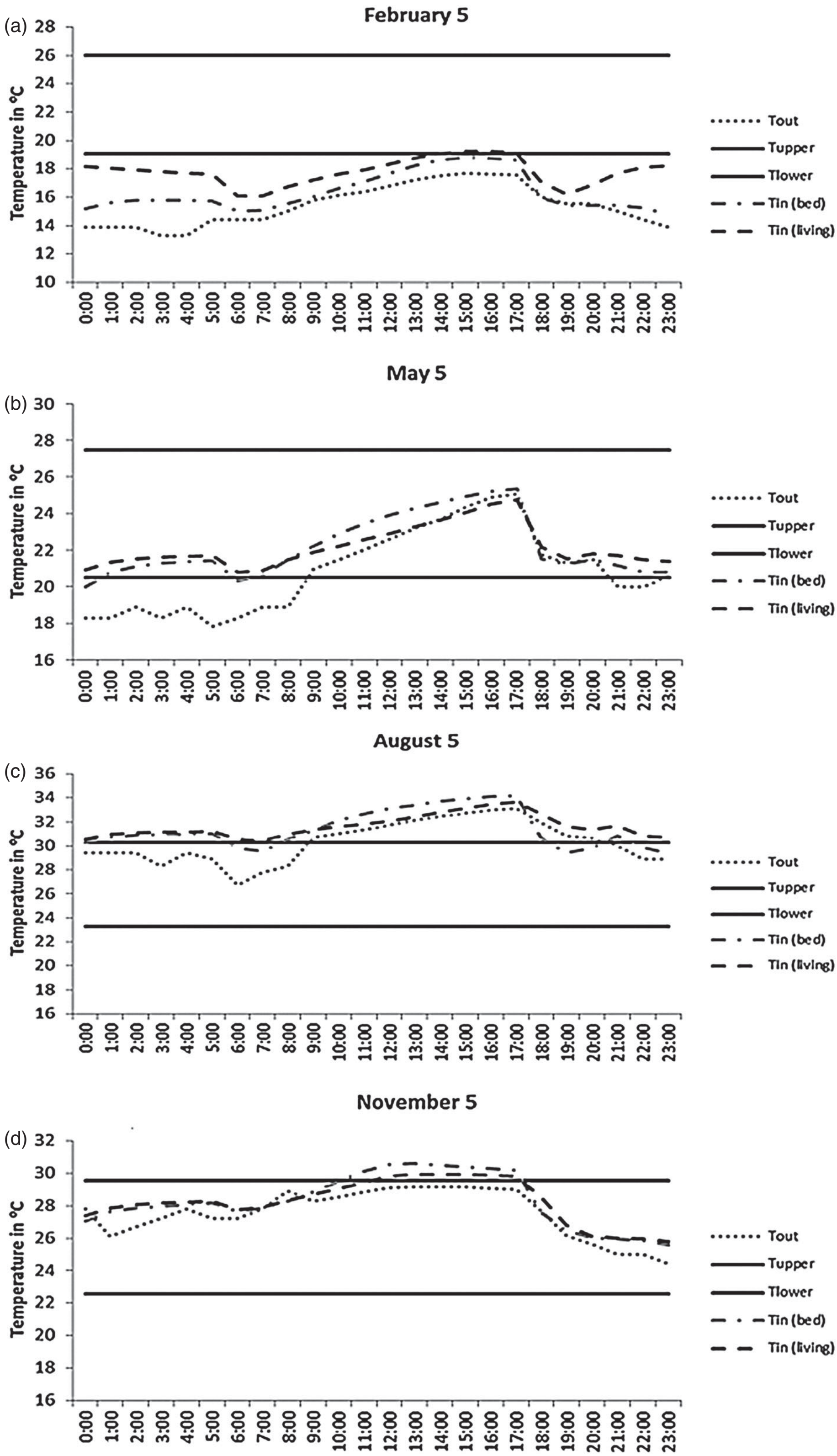


Figure 6. Daily temperature variation of mid seasons using base case, (a) Winter, (b) Spring, (c) Summer, (d) Fall.

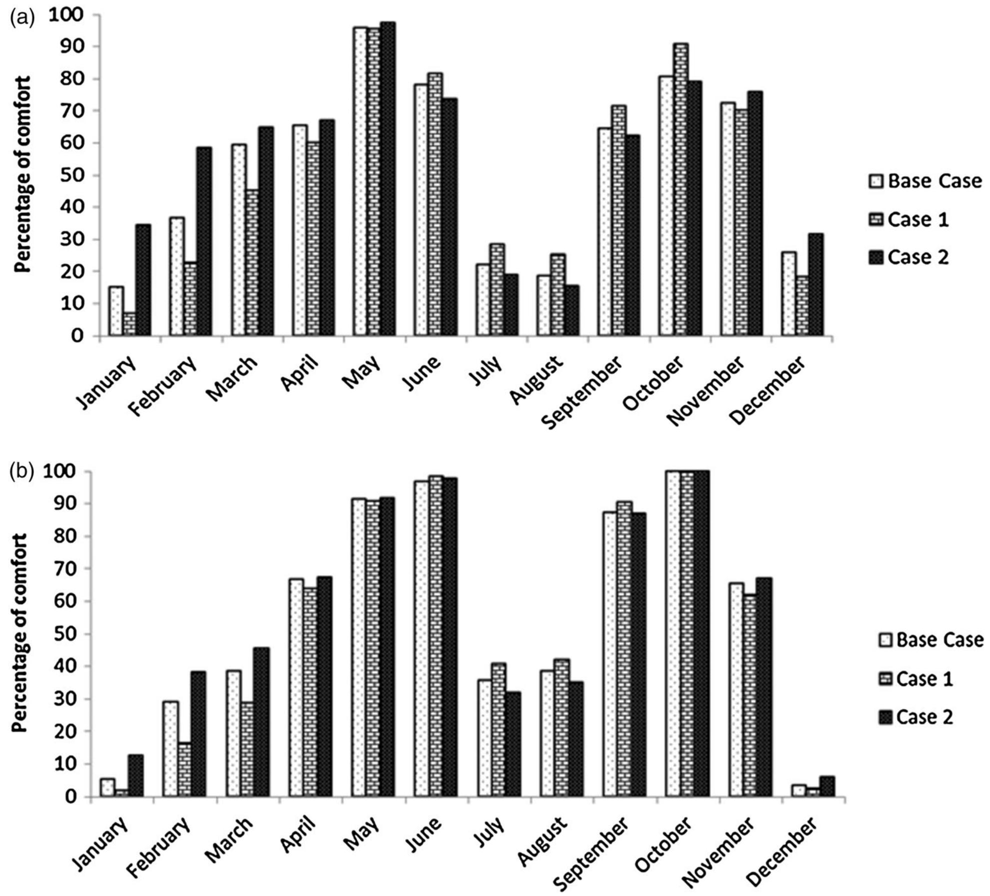


Figure 7. Monthly comfort percentage for the three building material constructions, (a) in the living zone, (b) in the bedroom.

During the months of January, February, and March representing winter season, the base case displays low comfort percentages of 15.05%, 36.61%, and 59.41% respectively in the living zone, and 5.38%, 29.17%, and 38.71% respectively in the bedroom zone. The temperature difference between the inside and outside of the building and high winds are the primary cause of heat loss in the winter months.

During April, May, June, October, and November representing both spring and fall seasons, the base case of both living and bedroom zones displays high comfort percentages up to 65.56%, 95.97%, 78.06%, 80.65%, and 72.5% respectively in the living zone and 66.67%, 91.40%, 96.94%, 100%, and 65.56% respectively in the bedroom zone. These mid-seasons are characterised by their mild weather. Air movement due to natural ventilation effectively improves the comfort conditions in these seasons.

## 5.2. *Effect of building envelop material on comfort hours*

Studying the effect of lower insulation and capacitance material (case 1), we observe that during July, August, and September (summer season) the overall comfort percentage increased to

Table 4. Monthly comfort hours and percentage in the living room for base case, case 1 and case 2.

| | Base case | | Case 1 | | Case 2 | |
|---|---|---|---|---|---|---|
| Month | No. of comfort hours | Percentage of comfort hours | No. of comfort hours | Percentage of comfort hours | No. of comfort hours | Percentage of comfort hours |
| January | 56 | 15.1 | 26 | 7.0 | 128 | 34.4 |
| February | 123 | 36.6 | 77 | 22.9 | 197 | 58.6 |
| March | 221 | 59.4 | 168 | 45.2 | 241 | 64.8 |
| April | 236 | 65.6 | 216 | 60.0 | 241 | 66.9 |
| May | 357 | 96.0 | 356 | 95.7 | 363 | 97.6 |
| June | 281 | 78.1 | 294 | 81.7 | 265 | 73.6 |
| July | 82 | 22.0 | 106 | 28.5 | 71 | 19.1 |
| August | 70 | 18.8 | 94 | 25.3 | 57 | 15.3 |
| September | 232 | 64.4 | 258 | 71.7 | 224 | 62.2 |
| October | 300 | 80.6 | 338 | 90.9 | 294 | 79.0 |
| November | 261 | 72.5 | 253 | 70.3 | 273 | 75.8 |
| December | 96 | 25.8 | 68 | 18.3 | 118 | 31.7 |
| Total | 2315 | 52.9 | 2254 | 51.5 | 2472 | 56.4 |

Table 5. Monthly comfort hours and percentage in bedroom for base case, case 1 and case 2.

| | Base case | | Case 1 | | Case 2 | |
|---|---|---|---|---|---|---|
| Month | No. of comfort hours | Percentage of comfort hours | No. of comfort hours | Percentage of comfort hours | No. of comfort hours | Percentage of comfort hours |
| January | 20 | 5 | 7 | 2 | 47 | 13 |
| February | 98 | 29 | 55 | 16 | 129 | 38 |
| March | 144 | 39 | 107 | 29 | 170 | 46 |
| April | 240 | 67 | 230 | 64 | 243 | 68 |
| May | 340 | 91 | 338 | 91 | 341 | 92 |
| June | 349 | 97 | 354 | 98 | 352 | 98 |
| July | 133 | 36 | 152 | 41 | 118 | 32 |
| August | 144 | 39 | 157 | 42 | 130 | 35 |
| September | 315 | 88 | 326 | 91 | 313 | 87 |
| October | 372 | 100 | 372 | 100 | 372 | 100 |
| November | 236 | 66 | 223 | 62 | 241 | 67 |
| December | 13 | 3 | 10 | 3 | 22 | 6 |
| Total | 2404 | 54.9 | 2331 | 53.2 | 2478 | 56.6 |

28.4%, 25.2%, and 71.6% respectively in the living zone and 40.7%, 42.2%, and 90.5% respectively in the bedroom zone. However, discomfort is still evident during January, February, and March representing winter season, where the overall comfort percentage decreased from that in the base case. During April, May, June, October, and November, representing both spring and fall seasons, case 1 also provided comfort and there was a small difference in the comfort percentages compared to base case due to the moderate outside temperature in these seasons. In April, May, and November, lower insulation material decreased the comfort to 60%, 95.7%, and 70.3% respectively in the living zone and to 63.9%, 90.8%, and 61.9% respectively in the bedroom zone.

Studying the effect of higher insulation and capacitance material (case 2) during July, August, and September (summer season), it was observed that comfort percentage slightly decreased compared to the base case. During January, February, and March representing winter season, the comfort percentage increased from that in the base case to 34.4%, 58.6%, and 64.8% in the living zone and to 12.6%, 38.4%, and 45.7% in the bedroom zone. During fall and spring months, there was a small difference between the base case and cases 1 and 2. In June, higher insulation material (case 1) displays less comfort percentages than the base case, reaching 73.6% in the living zone and 97.8% in the bedroom zone due to lower temperatures reached during the night-time. Similarly, in October, the comfort decreases to 79% in the living zone, while maintaining 100% comfort in the bedroom zone.

Clearly, natural ventilation is a feasible option in Beirut city during the fall and spring seasons with comfort hours (more than 60%). Changing the building envelope does not significantly change the comfort percentages during the fall and spring seasons when natural ventilation is used. However, increasing the $U$-value of the wall as well as heat capacity (case 2) has a significant effect during the winter season, especially in the living zone with an improvement of comfort. During summer time, the use of the massive wall had a negative effect on the comfort, but it was comparable to the positive effect during the winter season. Using low insulation (case 1) improved the comfort during the summer but significantly reduced comfort during winter.

It is clear from the aforesaid that the effect of higher insulation is more evident during the winter time where the comfort hours have almost doubled during January and February. The added value of using local natural building material is in lowering embodied energy (Olgyaya and Herdtb 2004; Yassine et al. 2012; Yassine et al. 2014). It is true that 100% comfort is not achieved during winter, but it is much easier to control personal comfort by using more clothing layers. However, for the hot humid months of July and August, there is an inevitable need of air conditioning and the use of higher insulation will decrease the HVAC consumption as compared to using typical construction material with low insulation. Since the overall yearly hours of comfort for the massive case 2 is better, we recommend its use, and if integrated with mechanical ventilation or conventional air conditioning, it can reduce the cost of energy consumption.

## 6. Recommendations and conclusion

This paper integrates assessment of utilising natural ventilation in Beirut residential area with thermal comfort. Using Beirut typical construction materials and Beirut occupants' behaviour in regulating the opening and closing of the windows established in a conducted survey, the work is indicative of considerable potential for saving energy by using natural ventilation instead of air conditioning.

The use of natural ventilation was found to be more effective for comfort with the use of locally available wall massive construction materials mainly in the moderate seasons of fall and spring. This recommendation is applicable to similar mesothermal climates. Using high insulation and capacitance material was recommended, achieving a yearly thermal comfort of 56.6% in the bedroom and 56.5% in the living zone.

## References

Abdurahiman, M. S. 1988. *HVAC and Climatic Design in the Arab Courtyard Houses*. Calicut, India: National Institute of Technology Calicut.

Ahmed, N. A., and K. Wongpanyathaworn. 2012. "Optimising Louver Location to Improve Indoor Thermal Comfort Based on Natural Ventilation." *Procedia Engineering* 49: 169–178.

Al-Shaali, R. K. 2002. "Maximizing Natural Ventilation by Design in Low Rise Residential Buildings using Wind Catchers in the Hot Arid Climate of UAE." Master thesis, University of Southern California, USA.

Arent, L. T., M. A. Paula, and E. Ghisi. 2011. "Thermal Comfort Analysis of a Naturally Ventilated Building." *12th International Conference of Building Performance Simulation Association*. Sydney, November 14–16.

ASHRAE. 2004. ASHRAE Standard 55–2004: *Thermal Environmental Conditions for Human Comfort*. Atlanta, GA: ASHRAE, 2004.

Awwad, E., B. Hamad, M. Mabsout, and H. Khatib. 2010. *Sustainable Construction Material Using Hemp Fibers – Preliminary Study*. 2nd International conference on Sustainable Construction Materials June 28–30.

Baker, N. 2011. Natural Ventilation: Stack Ventilation. RIBA. Accessed November 20, 2013. http://www.architecture.com/SustainabilityHub/Designstrategies/Air/1-2-1-2-Naturalventilation-stackventilation.aspx

Barclay, M. 2012. "The Interaction of Building Energy Use, Ventilation Performance and Urban Noise Under Future Climate Scenarios." PhD. Thesis, School of Architecture, The University of Sheffield.

Byblos. 2013. "Byblos Economic Research & Analysis Department, Lebanon This Week." *Byblos Bank sal*, no. 300: 1–2.

CDR. 2005. *CDR National Physical Master Plan for the Lebanese Territory*. Beirut, Lebanon: Council for Development and Reconstruction (CDR).

Chilton, A., P. Novo, N. McBride, A. Lewis-Nunes, I. Johnston, and J. Rene. 2012. "Natural Ventilation and Acoustic Comfort." *Proceedings of the Acoustics 2012 Nantes Conference*, Nantes, France.

de Dear, R. J., and G. S. Brager. 2002. "Thermal Comfort in Naturally Ventilated Buildings: Revisions to ASHRAE Standard 55." *Energy and Buildings* 34 (4): 549–561.

Doran, S., and E. Kilbride. 2000. *Safety and Health Business Plan, Field Investigations of the Thermal Performance of Construction Elements as Built*. Glasgow, UK: Building Research Establishment.

Eftekhari, M. M. 1998. "Natural ventilation: Impact of Wall Material and Windows on Thermal Comfort." *Building Services Engineering Research and Technology* 19: 43–47.

Eftekhari, M. M., and D. J. Pinnock. 1998. "Natural Ventilation: Airflow Measurements in a Lightweight Test Room." *Building Services Engineering Research and Technology* 19: 37–42.

ELARD (European LEADER Association for Rural Development) Coastal Zones. 2010. Vulnerability, Adaptation and Mitigation Chapters of Lebanon's Second National Communication, Climate Risks, Vulnerability & Adaptation Assessment. Beirut, Lebanon: Ministry of Environment/UNDP.

Elfordy, S., F. Lucas, and F. Tancret, Y. Scudeller, L. Goudet. 2008. "Mechanical and Thermal Properties of Lime and Hemp Concrete ("Hempcrete") Manufactured by a Projection Process." *Construction and Building Materials* 22 (22): 2116–2123.

Etheridge, D. W., and J. J. Zhang. 1998. "Dynamic Insulation and Natural Ventilation: Feasibility Study." *Building Services Engineering Research and Technology* 19: 203–212.

Gao, C. F., and W. L. Lee. 2010. "Influence of Window Types on Natural Ventilation of Residential Buildings in Hong Kong." *International High Performance Buildings Conference at* Purdue University, West Lafayette, Indiana, USA.

Ghaddar, N., K. Ghali, and S. Chehaitly. 2011. "Assessing Thermal Comfort of Active People in Transitional Spaces in Presence of Air Movement." *Energy and Buildings* 43 (10): 2832–2842.

Haggag, M. A. 2008. "The Use of Passive Cooling Strategies in Dubai Moving Towards Sustainability." *Proceeding of Ecocity World Summit 2008*. Dubai City, UAE.

Hall, K. 2006. *The Green Building Bible*. Vols. 1 and 2. 3rd ed. Carmarthenshire, Wales: The Green Building Press.

Herkel, S., U. Knapp, and J. Pfafferott. 2008. "Towards a Model of User Behaviour Regarding the Manual Control of Windows in Office Buildings." *Building and Environment* 43: 588–600.

High-performance Commercial Building Façades. 2013. *Double-skin Facades and Natural Ventilation*. Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley. Accessed November 03. http://gaia.lbl.gov/hpbf/techno_c3.htm

Holness, G. V. R. 2009. "Energy Efficiency in Existing Buildings – Our Greatest Opportunity for a Sustainable Future, Sustaining Our Future by Rebuilding Our Past." *ASHRAE Journal* 1: 1–4.

Houri, A. 2006. "Solar Water Heating in Lebanon: Current Status and Future Prospects." *Renewable Energy* 31: 663–675.

Houri, A., and S. Ibrahim-Korfali. 2005. "Residential Energy Consumption Patterns: The Case of Lebanon." *International Journal of Energy Research* 29: 755–766.

Larsen, T. S. 2006. "Natural Ventilation Driven by Wind and Temperature Difference." Thesis submitted for the degree of Ph.D., Department of Civil Engineering, Aalborg University.

Lebanese Construction Law. 2005. Law 15874, November 2005.

Linden, P. F. 1999. "The Fluid Mechanics of Natural Ventilation." *Annual Review of Fluid Mechanics* 31: 201–238.

Macroflo, MacroFlo Calculation Methods. 2012. *IES Virtual Environment 6.5*. Glasgow, UK: Integrated Environmental Solutions. http://www.iesve.com/website/var/assets/support/userguides/ve2012/thermal_reference/apachesimcalculationmethods.pdf.

Mathews, E. H., C. P. Botha, D. C. Arndt, and A. Malan. 2001. "HVAC Control Strategies to Enhance Comfort and Minimize Energy Usage." *Energy and Buildings* 33: 853–863.

van Moeseke, G., E. Gratia, S. Reiter, and A. De Herde. 2005. "Wind Pressure Distribution Influence on Natural Ventilation for Different Incidences and Environment Densities." *Energy and Buildings* 37: 878–889.

*Network CA News*. 2013. "Gulf's Largest Open-Air Square to be Built in Doha." *Network, CA News Network*, DMG World Medi1. Accessed November 21. http://www.constructarabia.com/construction-news/gulfs-largest-open-air-square-to-be-built-in-doha/

OEA. 2010. *Thermal Standards for Buildings in Lebanon 2010: Order of Engineers*. Beirut, Lebanon: OEA.

Olgyaya, V., and J. Herdtb. 2004. "The Application of Ecosystems Services Criteria for Green Building Assessment." *Solar Energy* 77: 389–398.

Pfafferott, J., and S. Herkel. 2007. "Statistical Simulation of User Behaviour in Low-energy Office Buildings." *Solar Energy* 81 (5): 676–682.

Pfafferott, J., S. Herkel, and M. Wambsganß. 2004. "Design, Monitoring and Evaluation of a Low Energy Office Building with Passive Cooling by Night Ventilation." *Energy and Buildings* 36: 455–465.
Serghides, D. K., and C. G. Georgakis. 2012. "The Building Envelope of Mediterranean Houses: Optimization of Mass and Insulation." *Journal of Building Physics* 36: 83–98.
Taleghani, M., M. Tenpierik, and A. van den Dobbelsteen. 2014. "Energy Performance and Thermal Comfort of Courtyard/Atrium Dwellings in the Netherlands in the Light of Climate Change." *Renewable Energy* 63: 486–497.
Tantasavasdi, C., J. Srebric, and Q. Chen. 2001. "Natural Ventilation Design for Houses in Thailand." *Energy and Buildings* 33: 815–824.
Tran Le, A. D., C. Maalouf, T. H. Mai, E. Wurtz, and F. Collet. 2010. "Transient Hygrothermal Behavior of a Hemp Concrete Building Envelope." *Energy and Buildings* 42: 1797–1806.
UNDP. 2005a. *UNDP Climate and Comfort: Passive Design Strategies for Lebanon*. Beirut, Lebanon: UNDP.
UNDP. 2005b. *UNDP Passive Climate and Comfort Design Strategies for Lebanon*. Beirut, Lebanon: UNDP.
USGBC Fact Sheet. 2010. "Natural Ventilation, A Road Map for Sustainable Building." Cascadia Chapter. Walker Andy Natural Ventilation. National Renewable Energy Laboratory.
Xu, B., L. Fu, and H. Di. 2009. "Field Investigation on Consumer Behavior and Hydraulic Performance of a District Heating System in Tianjin, China." *Building and Environment* 44 (2): 249–259.
Yassine, B., K. Ghali, N. Ghaddar, I. Srour, and G. Chehab. 2012. "A Numerical Modeling Approach to Evaluate Energy-Efficient Mechanical Ventilation Strategies." *Energy and Buildings* 55: 618–630.
Yassine, B., K. Ghali, N. Ghaddar, I. Srour, and G. Chehab. 2014. "Effectiveness of Earth Tube Heat Exchanger System Coupled to a Space Model in Achieving Thermal Comfort in Rural Areas." *International Journal of Sustainable Energy* 33 (3): 567–586.

## Appendix 1.

*Field survey on using natural ventilation*
For questions 1–8, please choose your correct answer:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1. Gender | Female | ☐ | Male | ☐ | | | | |
| 2. Age range (years) | $<$ 20 | ☐ | 20–35 | ☐ | 35–50 | ☐ | $>$ 50 | ☐ |
| 3.Type of residential building | Apartment | ☐ | Villa | ☐ | Dormitory | ☐ | | |
| 4. Residential Area ($m^2$) | $<$ 150 | ☐ | 150–250 | ☐ | $>$ 250 | ☐ | | |
| 5. Apartment floor | 1–3 | ☐ | 4–6 | ☐ | $>$ 6 | ☐ | | |
| 6. Number of occupants | 1–2 | ☐ | 3–5 | ☐ | 6–8 | ☐ | $>$ 9 | ☐ |
| 7. WWR | 10% | ☐ | 20% | ☐ | 30% | ☐ | 40% | ☐ |
| 8. External windows and door orientation | North | ☐ | South | ☐ | East | ☐ | West | ☐ |

9. Please indicate in the following 4 periods the hours in the day that you might open the windows in bedroom and living zones. Choose the number of hours for each period, or mark 0 if the windows will be closed in this period of time.

| | | | | |
|---|---|---|---|---|
| Living zone | | | | |
| A typical day during summer | Periods | | | |
| | 6am–12pm | 12pm–6pm | 6pm–12am | 12am–6am |
| | 6am–12pm (all open) | 3pm–6pm (partially open) | 6pm–10pm (partially open) | 0 (all closed) |
| Bedroom zone | | | | |
| A typical day during summer | Periods | | | |
| | 6am–12pm | 12pm–6pm | 6pm–12am | 12am–6am |
| | 6am–12pm (all open) | 12pm–3pm (partially open) | 8pm–12pm (partially open) | 0 (i.e. all closed) |

10. Please indicate the degree to which you open the window (window degree of opening profile) in each season.

| | Degree of opening | | | | |
|---|---|---|---|---|---|
| Season | 0 | 0.25 | 0.5 | 0.75 | 1 |
| Spring | | | | | |
| Summer | | | | | |
| Fall | | | | | |
| Winter | | | | | |