Performance of Natural Ventilation in Deep-plan Educational Buildings: Case Study

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ABSTRACT: This paper discusses the applicability, use and performance of natural ventilation and natural daylight in two educational buildings on two continents. It discusses actual measured data in the building compared with simulations made by the ASHRAE Thermal Comfort Model that was developed by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE). The buildings were the Harm A. Weber Academic Centre completed in July 2007 on the campus of Judson University in suburban Chicago, IL, and, Lanchester Library completed in August 2000 on the campus of Coventry University in Coventry, UK. Three sets of scenarios were used in the building measurements: summer, winter and mixed-mode-season. Both use significant amounts of natural ventilation and high thermal mass. The study had students carrying out their normal activities in studio while wearing regular clothes. A questionnaire and instrumentation were administered to record data on thermal sensation and preferences of the occupants. Both buildings have significant applications and use of passive design strategies that include natural ventilation, natural daylight and thermal mass. The strategies tackle the limitations of traditional natural ventilation and daylighting strategies and suggest directions for design in complex urban contexts. Computer modeling was used to assess the performance of the strategies in other types of buildings and building forms.

KEYWORDS: natural ventilation, dry-bulb temperature, humidity, energy-efficiency

INTRODUCTION

The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) defines "ventilation as the intentional introduction of air from the outside into ma building and it can be done either as (1) ***natural ventilation*** through open windows, doors, grilles, and other planned building envelope penetrations, and/or (2) ***mechanically or forced ventilation***" (ASHRAE, 2009, p. 16.1). Natural ventilation is driven naturally by pressure differentials. In the past fifty years, the use of natural ventilation in modern buildings has declined significantly because of the technological advancements in mechanical heating, ventilating and air-conditioning (HVAC) systems. The use of outdoor air flow into buildings to provide ventilation and space cooling has been in existence since time immemorial in different climates. Comfort and healthy indoor quality (IAQ) requires a careful balance between control of pollutants, supply of fresh air, exhaustion of unacceptable air and maintenance systems. Outside air must dilute and remove contaminated indoor air. Natural ventilation in primitive buildings traditionally relied on wind and thermal buoyancy of heated/cooled air. It was observed that "the thermal storage capabilities inherent in the mass of a building structure can have significant effect on the space temperature as well as on HVAC system performance and operation" (ASHRAE, 2012, p. 51.18). Night-time ventilation of thermal mass can dampen and delay transfer of heat and temperatures in building envelopes. Correct ventilation strategies can moderate indoor temperatures (Brandemuehl, Lepore, & Kreider, 1990; Wilcox, 1985) and reduce energy consumption in active and passive solar buildings (Newell & Snyder, 1990; Balcomb, 1983).

People in different cultures around the world have used these driving forces to modulate and transform indoor conditions to the desired thermal environment and to extract undesired indoor air contaminants (Rapoport, 1969). A fireplace in the center of a room provided fire for cooking, light for visibility and higher air temperature that accelerated buoyant indoor air. In most of the United States of America, residential buildings have historically relied on infiltration and natural ventilation (ASHRAE, 2012, p. 16.2). This technique was used to adjust indoor climate but has now grown to become highly sophisticated and mechanized in terms of energy estimating and modeling methods (ASHRAE, 2009, p. 19.1). First costs and maintenance costs have grown significantly recently. Annually, the demand and growth of heating and air-conditioning equipment is putting major demands on space for equipment rooms in buildings. "Of the total energy used in buildings in the US, 7% is for cooling and 3.2% is for ventilation" (Brown, Kline, Livingston, Northcutt, & Wright, 2004, p. 12). The total space required for mechanical, electrical, plumbing and fire

protection for life-safety ranges “between 4 and 9% of gross building area, with most buildings in the 6 to 9% range” (ASHRAE, 2012, p. 1.6). Mechanical technologies have become highly complex and expensive, needing large floor space area. Indoor air-quality and other health-related issues require greater concerns of indoor climate for occupants of all building types. Concerns are also growing concerning the need to reduce CO_2 emissions. Kyoto protocol bound highly industrialized and developed countries to reduce greenhouse gases at least 5% by 2012, improve energy-efficiency and promote the use of renewable energy (United Nations, 1998). Natural ventilation contributes to Kyoto requirements by promoting the use of renewable energy, reduction of the cooling load and promotion of thermal comfort (De Dear & Brager, 1998). Natural ventilation saves energy (Ogoli, 2006; Givoni, 1998) but it is only energy-based HVAC systems that have established standards (ASHRAE Standard 55, 2010; ASHRAE Standard 62, 2007) for prescriptive ratings.
The two deep plan buildings discussed herein are defined by a wall to floor height ratio of 8:1, i.e., horizontal distance on the shortest external wall to the floor to floor height. Deep plan buildings are efficient users of a given site. Deep plan multi-story buildings have special challenges for the applicability, use and performance of natural daylight and natural ventilation, a problem that usually necessitates the use of expensive large HVAC systems and artificial lights ((Bordass, 2001).

EXPERIMENTAL METHOD

This study examines two buildings, the Harm A. Weber Academic Centre (HAWAC) at Judson University (USA) and Fredrick Lanchester Library (FLL) at Coventry University (UK). Both buildings are educational and have significant application of passive solar design strategies that include natural ventilation, natural daylight and building thermal mass. HAWAC was completed in 2007 with a library, classrooms and offices in suburban Chicago, IL. The building has three broad modes of operation for three distinct annual seasonal changes: (1) mechanical heating and humidification primarily in winter, (2) mechanical cooling and de-humidification particularly in summer, and, (3) fully integrated hybrid passive solar heating and natural ventilation for the mid-season. It also uses a photo-voltaic system integrated into the southern façade. Using the taxonomy for stack-effect ventilated buildings proposed in a recent paper (Lomas & Cook, 2005), HAWAC uses center-in edge-out (C-E) approach in the library block with localized edge-in edge-out (E-E) ventilation of perimeter offices. The Fredrick Lanchester Library (FLL) uses both center-in edge-out (C-E) and center-in center-out (C-C) strategies. Both buildings have very deep floor plans with ventilation air-flow controlled by demand through automated controls in each zone.

Data-logging instruments were used to collect temperature, humidity and air-flow data from various locations of the buildings. Simultaneously, questionnaires were administered to determine thermal sensations from occupants of the buildings. The study utilized two most common ways of quantitatively expressing thermal comfort and thermal sensation in the terms of Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD) as developed in 1970 (Fanger, 1970) and then revised in 1975 (Humphreys, 1975).

OBSERVATIONS

3.1 Climate

HAWAC in suburban Chicago, IL (USA) is located at latitude 42.04°N and longitude 87.9°W. FLL is in Coventry (UK), at latitude 52.25°N and longitude 01.28°W. Both locations have semi-urban characteristics. In January, Chicago IL records a minimum temperature of -21.0°F (-5.8°C) and average maximum temperature of 45.32° F (7.4°C), and correspondingly in July, it experiences a minimum temperature of 53.42°F (11.9°C) and maximum temperature of 90.86°F (32.7°C). On the other hand, Coventry UK in January records a minimum temperature of 28.22°F (-2.1°C) and average maximum temperature of 50.72°F (10.4°C), and correspondingly in July, it experiences a minimum temperature of 43.52°F (6.4°C) and maximum temperature of 75.74°F (24.3°C). The local climate in Coventry is moderately cold during the winter months with 5448 heating degree days (base 65°F) and 48 cooling degree days (base 65°F), a ratio of 113:1. The local climate in Chicago is severely cold during the winter months with 6498 heating degree days (base 65°F) and 830 cooling degree days (base 65°F), a ratio of 8:1. See Table 1.

Table 1: Dry-bulb temperatures and degree-days base 65°F – compared

	Chicago, IL				**Coventry, UK**			
	Maximum Temperature		Minimum Temperature		Maximum Temperature		Minimum Temperature	
	°F	°C	°F	°C	°F	°C	°F	°C
Jan	45.3	7.4	50.7	10.4	28.2	-2.1	-5.8	-21
Jul	90.9	32.7	75.7	24.3	43.5	6.4	53.4	11.9
HDD65	6498				5448			
CDD65	830				48			

Both locations have semi-urban characteristics. In Chicago, the average maximum temperature swing between winter and summer is about 96.66°F (35.9°C) and correspondingly in Coventry the average maximum temperature swing between winter and summer is about 47.52°F (8.6°C). It appears from these data that Coventry has more opportunities for the applicability and use of natural ventilation. However, because Chicago has a higher mean diurnal range in air temperature of 9°C (16°F) in the spring and fall, it has better opportunities for night-time ventilation for thermal mass. The key features of the two buildings are summarized here below. Both buildings were designed by Short & Associates and completed in August 2000 (FLL) and July 2007 (HAWAC). They both have four main floor levels each.

3.2 Fredrick Lancaster Library (FLL) in Coventry, UK

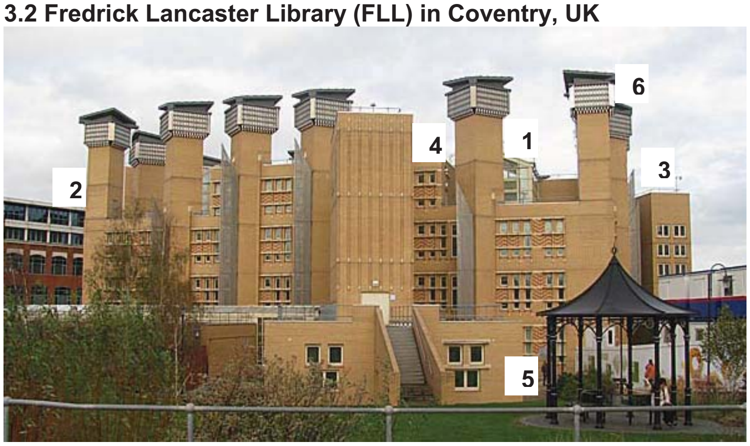


Figure 1: Main View of Fredrick Lanchester Library in Coventry University, England

The view of ventilation stacks (Figure 1) provide an indication for the air flow patterns for FLL. The corner light wells are the major areas for fresh air supply (1) with central light wells provide a means to exhaust air (2). Perimeter stacks (3) are also used to exhaust air. Air intakes to plenum around perimeter (4) joins directly to rooms for air supply (5) and exhaust (6). Air transfer ducts are acoustically treated to minimize noise. The larger rooms are arranged to span from the light well to the perimeter. The light wells provide natural ventilation and natural daylight into the interior spaces. The building has offices, library and teaching areas which for security reasons has the building façade sealed. The windows are clear low-emissivity double glazing and are shaded by the stacks, stair towers and vertical metal fins. The perimeter has radiators with thermostats, and exhaust dampers at high level. Solar shaded light-well for natural ventilation introduces into the interior spaces so that stack-effect natural ventilation and natural daylight. The floor plate measures 50 m x 50 m (164 feet x 164 feet).

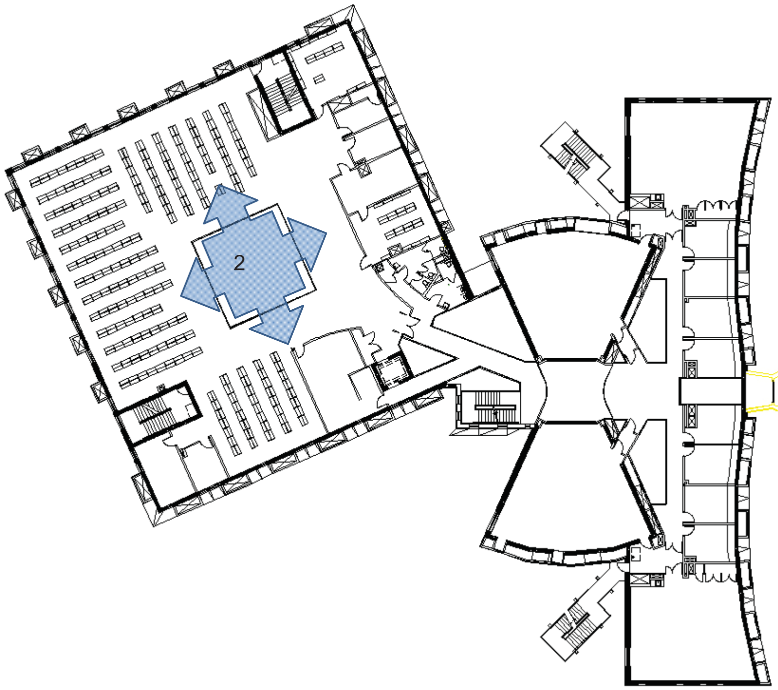
3.3 Harm A. Weber Academic Centre (HAWAC) in Elgin, IL

HAWAC integrates natural ventilation with standard HVAC system. It has an extensive landscape area with on-site storm water management and native prairie area on the south-side. HAWAC is designed to utilize night time ventilation, coupled with exposed thermal mass and sun-shading devices. The building is constructed with slightly higher insulation levels than standard buildings in this climate in order to reduce the mid-winter (December to February) heating energy loads. However, during spring period (March to April) and fall period (October to November) the building demands more heating energy because the window shading devices (needed for thermal control in the summer) excludes useful solar gain. The schedule of net floor areas is shown in Table 2. The building has twenty exterior exhausts for airflow paths. The dominant building material for both wall and floor/ceiling elements is thermal mass (12" thick concrete) to levels higher than commonly found in local buildings. In the mixed hybrid mode, the air-handling unit is shut-off. Air flow is driven mainly by natural buoyancy of warm air due to internal heat gains so that indoor temperatures remain between 68°F (20.0°C) and 80.6°F (27°C) for comfort. Figure 2 and 2 illustrate the supply air ducts embedded in the façade (1), exhaust air ducts embedded in the façade (2), return air duct from the roof plenum (3), riser ducts supplying the classrooms (4), exhaust ducts connected to roof-level plenum (5) and central supply to the library (2). The floor plate with a light well measures 35.5 x 35.5 m (116 feet x 116 feet).

Table 2: Schedule of floor areas in Harm A. Weber Academic Centre (square feet)

	Level1	Level 2	Level 3	Level 4	**Total**	Net Ratio
Library "Block"	6350	10585	10645	10330	**37910**	47%
Bowtie "East"	785	1320	1312	1315	**4732**	6%
Bowtie "West"	1020	1300	1315	1300	**4935**	6%
Office Bar	4014	3595	3725	3850	**15184**	19%
Hall	2924	3090	2281	2350	**10645**	13%
WC	1007	288	315	409	**2019**	2%
Mechanical Room	5216	100	68	85	**5469**	7%
TOTAL	**21316**	**20278**	**19661**	**19639**	**80894**	
[Light well]		[805]*	[805]*	[805]*		

Figure 2: Cladding (arrows) indicates location of stacks for natural ventilation in HAWAC

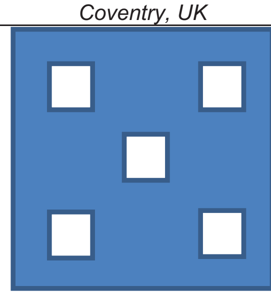
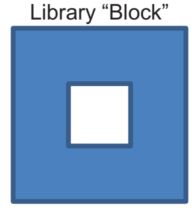


The building has three air-handling units on level one for a fully functioning HVAC system. Return air ducts connecting the exhaust air plenum to the air-handling plant and mechanical supply to the air inlet plenum are also on level one. The building has several air intake locations to the mechanical rooms and fresh air for natural ventilation for cellular office each with an acoustic attenuator box, damper and reheat coils.

Figure 3: Floor plan indicating location of vertical stacks for natural ventilation in Harm A. Weber Academic Centre

3.4 Comparison of key features of the two natural ventilated buildings

Table 7: Comparison of key features

	Fredrick Lancaster Library (FLL) in Coventry, UK	*Harm A. Weber Academic Centre (HAWAC) in Elgin, IL*
Footprint Gross floor area Floor to ceiling height	 50 m x 50 m (164 feet x 164 feet) 9103 m^2 (97,984 ft^2) 3.9 m (12.9 feet)	Library "Block"  35.5 m x 35.5 m (116 feet x 116 feet) 4660 m^2 (50,160 ft^2) 4.0 m (13.1 feet)
U-values (Roof) U-values (Wall) U-values (Windows)	0.18 W/m^{2}K (0.0317 BTU/h ft^2 F) 0.26 W/m^{2}K (0.045789 BTU/h ft^2 F) 2.00 W/m^{2}K (0.35222 BTU/h ft^2 F)	0.25 W/m^{2}K (0.044028 BTU/h ft^2 F) 0.25 W/m^{2}K (0.044028 BTU/h ft^2 F) 2.60 W/m^{2}K (0.457887 BTU/h ft^2 F)
Window shading	Perimeter stacks, metal fins	External window reveals
Air supply light wells Advanced Natural Ventilation (type)	4 light wells Centre in edge out (C-E) and Centre in centre out (C-C)	1 light well Centre in edge out (C-E) and Edge in Edge out (E-E)
Heating and Cooling Method	Natural	Hybrid Natural and HVAC
Air supply light-wells	Square shape, glazed at the top with moveable blind shading, clear single glazing sides and dampers for air outlets	Square shape, glazed at the top with moveable blind shading, clear single glazing sides and top-hung windows for air outlets

ANALYSIS AND DISCUSSION

4.1 General Observations

The ASHRAE winter design dry-bulb temperature for Chicago is -4°F (-20°C). The design goal is to provide appropriate levels of insulation and a tight building envelope. Thermal mass is passively cooled by night-time ventilation by the concept of "balancing of time" so that temperature swings are created to shift night-time coolness to daytime moments when cooling is needed. The roof plenum is used to exhaust air from lower floors to minimize gaining too much heat energy content. In summer mode, the building switches into the mechanical cooling and de-humidification modes of operation to ensure it does not exceed the upper limit of ASHRAE *Standard 55* comfort zone. Dampers at the inlet to the plenum and in exhaust outlets in the roof are closed so that return air ducts from room plenums remain open.

A parametric analysis of the data shows how the outputs change when they are varied one at a time. The responses to the questionnaires appear to suggest that occupants are generally comfortable in the building in summer and also in the winter. PMV is calculated using the formulation published in ISO-7730. The building is occupied daily between the hours 6:00 AM and 2:00 AM. In summer, most students are away on vacation but evidence appears to indicate that indoor air temperatures are slightly higher than thermal comfort limits. In the winter period, the building utilizes a conventional heating system but it may be observed that 73% people voted for no change, 18% voted for a warmer indoor environment while 9% voted for a cooler indoor environment.

4.2 Stack-effect ventilation analysis

The observed supply air temperature at the air-handling unit is 11 °C (52 °F) with a target of entering the occupied space at 16 °C (60 °F). Measured air indoor and outdoor dry-bulb temperatures with some stratified temperatures are shown in Figure 4. It shows that in the summer (June 25) indoor temperatures are well within the comfort zone. The average outdoor modulation is about 10 degrees lower than indoor temperature at 5:00 AM and about 7 degrees higher than the indoor condition at 3:00 PM. For this reason, the set-point temperatures for the two buildings are 68 °F (20.0 °C) in winter and 78 °F (25.5 °C) in the summer. This wide range implies that the buildings extend their passive solar capabilities before starting heating, ventilating and air-conditioning (HVAC) systems. It appears that the adaptive model of thermal comfort in which cross-ventilation and giving the occupants personal control of their own environment helped to increase their thermal comfort sensation to adapt better to indoor temperatures. A person's experience of a place is a multi-variate phenomena and the adaptive model shows that thermal perception is affected by circumstances beyond the physics of the body's heat-balance, such as climate setting, social conditioning, economic considerations and other contextual factors. Observations of the data on thermal comfort in the Harm A. Weber Academic Centre appear to suggest that when people have a wide range of adaptive factors, their sense of comfort increases.

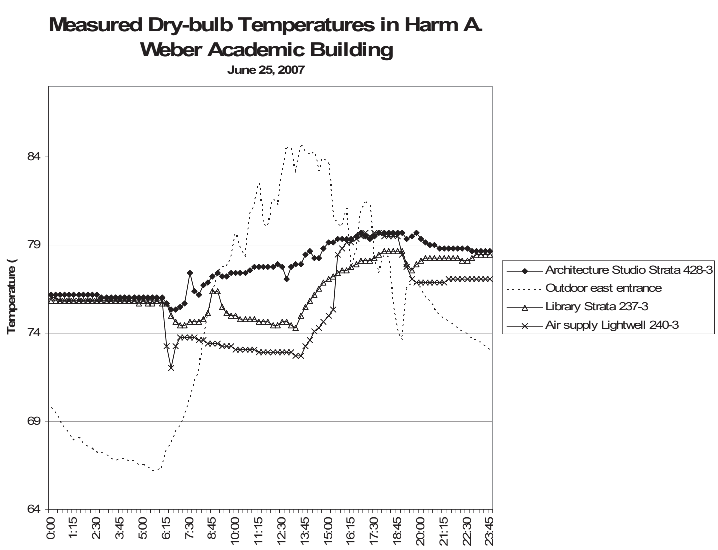


Figure 4: Measured dry-bulb temperatures in various areas

Some students' comments:

"Studio gets cold at night. It seems that fresh air is not sufficiently conditioned before entering the space (too hot in summer, too cold in winter)."

"The building is too cold at night. The air is fresh and clean, but often noticeably uneven throughout the building."

"The building whines like a 'banshee' due to night time air ventilation, usually after 10pm and early opening morning hours".

Lomas discussed the sizing equations for a simple stack-effect ventilation system whereby a low level inlet supplies a given space to be cooled alongside a high level outlet into a stack and mass rate are given by the following equations (Lomas K. J., 2007):

$$m = \frac{QA_1}{C_c \Delta T}\ (m^3/s) \qquad \text{and} \qquad A_2 = \frac{m}{v}\ (m^2) \qquad (1)$$

Where m is volume flow of air (m^3/s), Q is heat gain (W/m^2) , A_1 (m^2) is total floor area, ΔT (K) is temperature difference, C_c is volumetric heat capacity of air (1200 J/m^3 K), A_2 is area of the ventilation opening, and v (m/s) is air speed. Combining the equations above yields the following relationship:

$$\frac{A_2}{A_1} = \frac{Q}{v C_c \Delta T} \times 100\% \qquad (2)$$

Using values of v=0.5 m/s, C_c=1200 J/m^3 K, ΔT=5 K and several suggested values of heat gains (Lomas K. J., 2007, p. 174), the ratio of measured and compared area of light-well to total floor area is given in Table 3.

Table 8: Ratio of area of light-well to total floor area in HAWAC

Q (W/m^2) Total Heat Gains	V (m/s)	C_c (J/m^3 K	ΔT (K)	Observed Ratio (occupied) (A_2/A_1)	Calculated (design stage) ratio (A_2/A_1)
20	0.7	1200	5	0.48%	
30	0.7	1200	5	0.71%	0.7%
40	0.7	1200	5	0.95%	
50	0.7	1200	5	1.19%	1.2%

Table 3 shows a comparison of the ratio of the area of light-well to total floor area. A previous study (Lomas K. J., 2007) was made to compare as-built and target design open areas that appear to suggest that the target areas may be somewhat larger than needed. Air flow speeds have been observed in the actual building as being between 0.3 m/s (60 FPM) and 0.7 m/s (137 FPM) which yield values slightly lower than anticipated.

4.3 Thermal Comfort Analysis

The comfort standard for the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), is ASHRAE *Standard 55-2010* entitled "Thermal Environmental Conditions for Human Occupancy". The standard is mainly a prescriptive standard intended for occupants with primarily sedentary activity. It specifies the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants in a variety of building types.
In winter, temperatures ranging from 20 to 23.5°C (68 to 74°F) at 60% relative humidity (RH) and 20.5 to 24.5°C (69 to 76°F) at 2°C (36°F) dew point are considered comfortable. In summer these ranges are 22.5 to 26°C (73 to 79°F) at 60% relative humidity (RH) and 23.5 to 27°C (74 to 81°F) at 2°C (36°F) dew point.

Air temperature and humidity are two most dominant environmental factors in thermal comfort. For most of the year, the building has medium relative humidity (30% to 60%) implying that it does not have high impact on human discomfort. The human body has an in-built mechanism to regulate itself through metabolic processes. When heat output is less than heat input, then adaptive factors like a change of clothing insulation, activity and change of room location become important control mechanisms. When the building can control its own indoor climate through passive solar heating passive cooling strategies, it saves overall building energy and enhances human comfort.

The preferred method of study for thermal comfort in the Harm A., Weber Academic Centre and the Fredrick Lancaster Library was the adaptive model since it allows occupants a large control of their ambient environment. Adaptive models include the variations in outdoor climate for determining thermal preferences indoors. Adaptive models have been developed that fit sensation to data based on field investigations to thermal comfort in different climates. The adaptive model is the most effective way of assessing passive solar buildings, or what is sometimes called “free-running” buildings. The adaptive model allows people to make adjustments to their clothing, activity, posture, eating or drinking, shifting position in a room, operating a window or shading device, or other “adaptive opportunity” in order to achieve or maintain thermal comfort. Many studies (Givoni, 1998) (De Dear & Brager, 1998) (Ogoli, ARCC Research Conference Spring 2007) demonstrate that when people are allowed greater adjustment and control over their own indoor environment, it extends the comfort zone. The adaptive model acknowledges that the occupant is not just a passive recipient of the environment but an active member. See observed results shown in Figure 5 and 6.

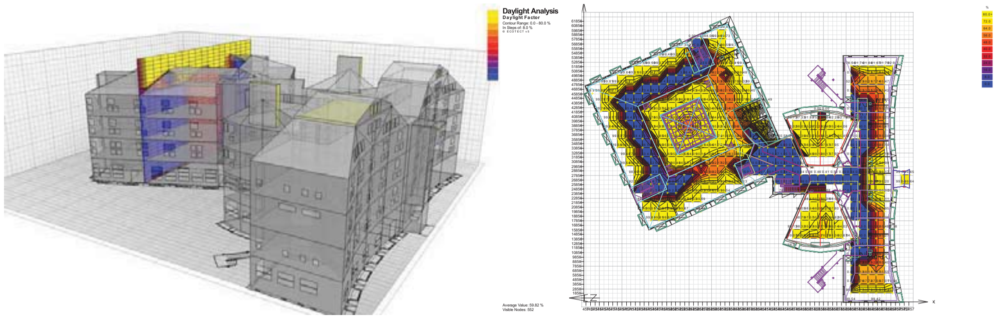


Figure 5: Air-flow, natural daylighting, thermal comfort and energy-efficiency analysis in Harm A. Weber Academic Centre

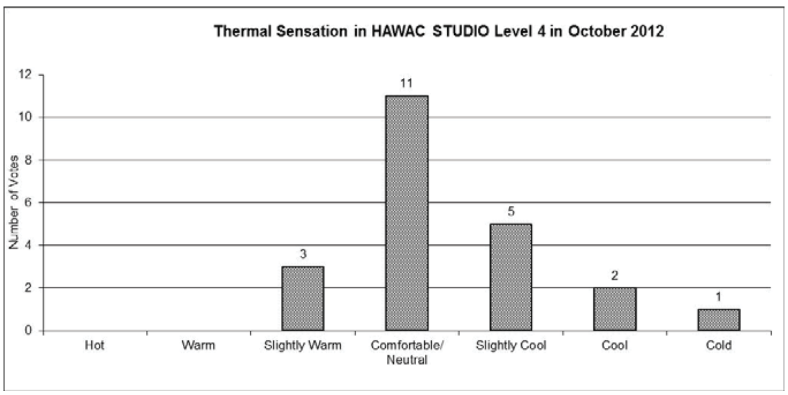


Figure 6: Indoor air quality in naturally ventilated HAWAC Library

CONCLUSIONS

The Harm A. Weber Academic Centre and the Frederick Lancaster Library are deep plan and they use generally less annual energy than similar buildings in their climates. Some important contributory factors include the use of high thermal mass that provides thermal inertia, building orientation that is within 30° due south, use of natural ventilation, use of natural daylight and use of deep-recessed windows. The most innovative and unique feature of these buildings are the mixed-mode, natural ventilation system. In the Harm A. Weber Academic Centre, HVAC systems are needed only 48% of the occupied hours of the year. The Lancaster Library uses more than 50% of the occupied hours because of the significantly milder climate. The use of natural ventilation, natural daylight and thermal mass altered the period for which active mechanical cooling energy is needed. Hybrid natural ventilation is an applicable strategy in an academic building in the climate of Chicago, IL and Coventry, UK. The performance of natural ventilation and daylight in deep-plan buildings is improved through the use of operable windows, doors, and stack-effect ventilation strategies that serve also as a large natural light-well.

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