Bridging the gap between energy consumption and the indoor environmental quality of a 1960s-educational building

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 132 (2017) 87–92

Energy Procedia

www.elsevier.com/locate/procedia

11th Nordic Symposium on Building Physics, NSB2017, 11-14 June 2017, Trondheim, Norway

Bridging the gap between energy consumption and the indoor environmental quality of a 1960s educational building

Xi Wen Leong[a], Emmanuel A. Essah[a]*

[a]School of Built Environment, University of Reading, Reading, RG6 6AW, UK

Abstract

The fundamental purpose of a building has evolved from merely providing protection from external environmental climate to more emphasis on integrating building services through building regulations to provide the synergy of comfort, efficiency and safety to the indoor environment. This research recognizes the rising demand and increasing quality of indoor environmental quality (IEQ) in the modern society compared to the acceptable level of previous traditional buildings. Generally due to its varied operations, educational buildings, in this case University libraries have its own set of challenges and barriers such as minimizing damages and decay of books and maintaining indoor conditions with an oversight of providing good IEQ to occupants. This paper presents a detailed evaluation of a 1960s-educational library with 24-hour access at the University of Reading. Through *in-situ* measurements, modelling and simulations of the building's energy consumption, IEQ parameters and occupancy patterns, investigations have been performed. Varied scenarios using the Integrated Environmental Solution (IES) software were also investigated. The findings illustrate that due to mixed façade configuration (i.e. sandstone and bricks) there is the unflinching need to balance aesthetics of the facade and functionality of a building to reduce excessive energy use via heating, without compromising on occupant comfort and well-being Although it is envisaged that refurbishing the library building will provide energy savings of up to 40%, this is farfetched and can only be achieved at the detriment of occupant comfort levels as evident in the simulation results, where these savings could not be realised. This paper further discusses the methods, scenarios, and results of ensuring good IEQ, comfort and energy efficiency are not been seen as mutually exclusive. This study forms part of ongoing research into the impact of educational buildings.

Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics.

Keywords: University Library; Energy; Indoor Environmental Quality; Modelling

* Corresponding author. Tel.: +44-0-118-378-8563
E-mail address: e.a.essah@reading.ac.uk

1876-6102 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics
10.1016/j.egypro.2017.09.643

1. Introduction

It is well documented now that over the years the building sector has accounted for 40% of the annual global energy consumption and 30% of greenhouse gases emissions [1]. Notably, in the UK aside domestic buildings, the non-domestic sector (industrial, commercial and public buildings) which consists of over 2 million buildings accounts for about 17% of total UK energy consumption. Commercial and public buildings (including educational buildings) contribute to 13% of the non-domestic energy consumption with continuously growing figures [2] due to an estimated 44% growth of student enrolment over the past 10 years across 200 universities [3]. More than 75% of these existing non-domestic buildings are dated pre-1980s where energy efficient strategy was not paramount [4]. It is estimated that by 2050, most of these buildings will remain in existence [5]. In addition, with a continual shift towards energy efficient buildings, the uptake of building regulations continues to be an essential requirement [6]. Therefore, the need to consider potential measures to maintain the structure of the building and attain efficient energy conservation has increasingly become important. Achieving this not only reduces costs but minimize the environmental impact by reducing emissions of carbon dioxide (CO_2) and other gases associated with global warming [7]. To date many studies have discussed energy saving methods for buildings most of which have 'fixed time' usage (say 8am-6pm) whereas there is very little on 24-hour access buildings [8]. In this paper, various issues of refurbishment, energy consumption and how it impacts on the indoor environment (IE) of a 24-hour access educational building is discussed.

1.1. Educational Buildings: Challenges in bridging the performance gap

The provision of suitable indoor environmental conditions are requirements for comfort and health of human beings, especially since human beings spend on average, 87% of their time in a building [6]. The impact of poor indoor environmental quality (IEQ) as a result of high indoor pollution, very low or high indoor temperatures, lack of daylight, excess noise, indoor air quality and thermal comfort [9] has detrimental effects on occupants. However, in todays' building designs, emphasis is placed on achieving energy savings when constructed, with less emphasis on the IEQ factors. This is observed to have a negative consequence on indoor conditions hence in the technical guide of CIBSE -TM54, it has been suggested that comfort and energy efficiency should not be seen as mutually exclusive [10]. In the context of Universities, nowadays regarded as 'small cities' because of its size, population and varied activities within the campuses, there is always a fine line between optimizing IEQ and/or energy savings. Nevertheless, the composition of such institutions results in high energy consumption amidst ensuring sustainability is still a priority. In a recent study, it has been noticed that changes to building regulations have influenced energy use in public buildings including Universities, with about 40% reduction. Although it is still uncertain to what extent adequate IEQ is achieved. This more so because educational buildings are characterised with a range of continually changing users, varied activities, and population density. With this post design uncertainty, it becomes more complex if such educational buildings (i.e. university libraries) are open for 24 hours a day, all week due to daily dynamic changes.

The operation of university libraries (UL) requires increasing energy use, maintenance, acceptable levels of IEQ while ensuring low energy cost and low emissions [11]. The design of such facilities with energy conservation in mind does have an impact on how IEQ is optimized. The fact that existing information is insufficient and lacks consistency, makes it difficult to understand the underlying changes that affect the influencing parameters [12]. As a result, despite the fact that understanding occupancy patterns and use of ULs is complex, it is worth studying with the integration of building simulation software. This is for modelling and prediction to inform the initial stage of the buildings design. The fact that the main parameters influencing ULs is unclear, understanding the complex relationship between design, energy demand/consumption, occupancy behaviour and coupled with 24-hour access, without compromising the quality of the IE is essential. To bridge this gap, *in-situ* measurements and building simulation modelling are two major methods used and discussed in this paper.

2. Methodology

This research focuses on the University Library (UL) located at the Whiteknights Campus of University of Reading (UoR) in the South-East of England. The 5-storey building is constructed with a combination of masonry-brick and sandstone wall, single-glazed windows and a total floor area of 9,774 m^2. Built in the 1960s, the building has a district heating system, with 24-hour access. Two main methods were considered for this study; experimental methods and modelling. In-situ measurements were designed to collect data of the IEQ parameters as well as outdoor conditions. These values were used to calculate the thermal comfort index; Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). The simulated results were verified/calibrated using experimental results and the monitored annual energy consumption. The actual energy data was provided by the University through Building Management System (BMS) that gives aggregate values. In addition, different scenarios were modelled with adjusted defining parameters to investigate the impact on the IE as well as the resulting energy use of the building (which is difficult through measurements).

2.1. Experimental Methods

In order to understand the variation in IE of the building, measurements were carried out over two seasons; May-June (Phase 1) and September-October (Phase 2) as illustrated in Table 1. These were developed to capture variations due to UoRs heating (1 October – 30 April) and cooling (1 June – 31 August) seasons. May and September are defined as the 'shoulder' periods (that is a period when the control conditions can be varied based on any extreme external weather changes).

Table 1. In-Situ Measurement Period at the Library in 2016

Month	**May**		**June**								**September**			**October**												
Dates	**30**	**31**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**28**	**29**	**30**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
UoRs Control	Shoulder		Cooling Season								Shoulder			Heating Season												

The IEQ parameters were measured using several sensors. Temperature and relative humidity (RH) were measured internally and externally using Lascar USB sensors and HOBO MX Logger (which also measured CO_2 concentrations). Measurements were at 5 minutes interval placed a height of 2.0 m [8]. Using CO_2 concentration, the ventilation rate of the Library was calculated using the decay method. Testo 435-2 and 4 in 1 multi environment meter were used to measure air velocity and noise respectively at 1.1 m. Additionally, the illuminance of lighting (for daylighting and artificial lighting times) was measured using the LX-1309 Light meter to investigate the significance of natural daylight. For conditions of study, assumptions were made for the metabolic rate (1.0 met) and sample data visually of clothing value (0.74 clo May-June, 1.0 clo September-October) were obtained and estimated [13]. From the results, PMV and PPD index were calculated as stipulated within BS EN 15251:2007 [14].

2.2. Building Energy Simulations

To replicate the current use of the building design, functionality and seasonal variations, a virtual model of the library was developed using Integrated Environmental Solutions (IES) software from floor plans obtained from UoR. Foot falls were taken to provide the necessary occupancy profiles. Fig 1 shows a picture of the library (a) and the IES models (b-e). The Virtual Environment of IES, a building energy simulation software was used for the numerical modelling and simulation that is otherwise, not possible through experimental methods.

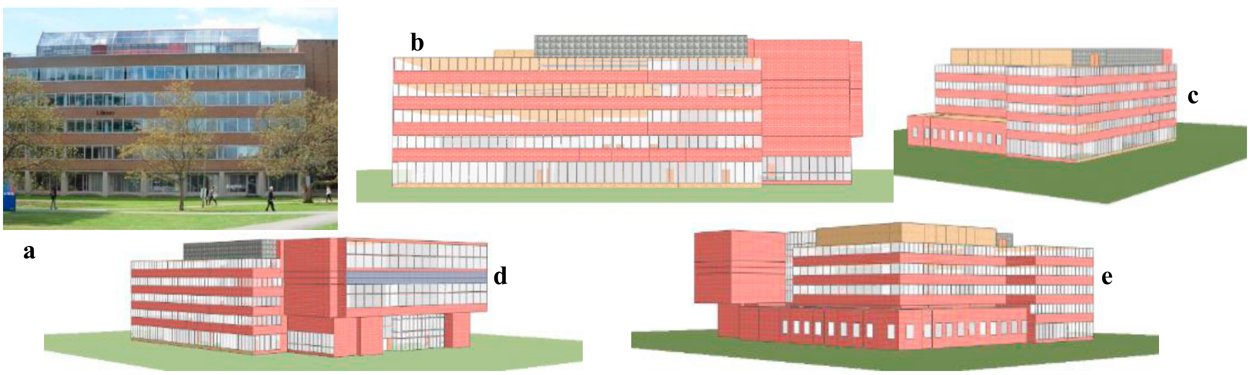

Fig. 1. (a) Illustrates a photograph of the UoR Library; (b) Modelled in IES; (c-e) IES models of the Library- of different views

The principles of IES is based on replicating a building's response to the external and internal conditions over varying time (dynamic simulation) using mathematical or physical models. The IES model was used to analyse the performance of the UoR Library based on location orientation, ventilation types, glazing etc. Table 2 shows the scenarios proposed to investigate the energy consumption and the consequent impact on the IE of the Library. Scenarios are guided by referenced literature.

Table 2. Proposed Scenarios based on existing model

Scenario	Description	Additional Comments
1	**Glazing:** Replacement of single to double-glazed windows	U-values 5.66 W/m^2K reduced to 2.68 W/m^2K with Inlet Gas Fill
2	**Lighting**: Changes in operation hour	Reduced use of lighting from 24-hour to 16 hours (16:00 to 8:00)
3	**Glazing and Lighting**	Combination of Scenario 2 and 3
4	**Efficiency:** Use of more efficient HVAC system	Efficiency of the system increased to 85 – 90% (improved by 25%)
6	**Ventilation Types:** Natural ventilation (NV)	1.5 ACH
7	**Ventilation Types:** Natural ventilation (NV)	3 ACH

3. Technical Analyses

3.1. Thermal Comfort (Temperature, RH, PPD and PMV)

Table 3 shows a summary of the measured results compared to recommended values from CIBSE [13]. The high temperatures recorded during phase 1(summer) are as suggested by CIBSE [13] for buildings without mechanical cooling during summer. Measurements for Phase 2 were performed during the heating period. The measured data, though slightly higher than CIBSE recommended values, they were constantly influenced by the external condition and the need to offer heating (phase 2). These had corresponding impact on the RH values. The data obtained were subsequently used as input values to calculate the PPD and PMV using simplified tool (CBE Thermal Comfort tool).

Table 3. Range of measured values for temperature and RH

Phase 1 Temperature (°C)			Phase 1 RH (%)			Phase 2 Temperature (°C)			Phase 2 RH (%)		
Measured		CIBSE	Measured		CIBSE	Measured		CIBSE	Measured		CIBSE
Outdoor	Indoor	Indoor	Outdoor	Indoor	Indoor	Outdoor	Indoor	Indoor	Outdoor	Indoor	Indoor
10 - 27	20 - 26	24 - 25	47 - 98	32 - 63	40 -60	2 - 25	20 - 25	22 - 23	39 - 98	33 - 64	40 -60

The pods (Fig 2) are designed to provide alternative study environment (enclosed) for group studies ensuring privacy, isolating any possible noise arising from within. These are located in the open plan study area and though. Measurements were only undertaken during September-October (due to availability), it was observed that the temperature in the pod is 2.6°C to 7°C warmer than other areas of the Library with prolonged duration of temperature recorded at 29°C. With an average air temperature of 25.7°C (peaking at 31°C, and 12% of the time above 28°C) and RH of 44.4%, the pod had the highest PPD (16%), which is considered as categories IV, as illustrated in Table 4. Aside this CO_2 levels were constantly above the recommended minimum of between 1500 – 1600ppm (CIBSE level, with a recorded maximum of 2047ppm. From this result the IEQ within the pods are poor, contradicting the purpose and design of these pods. Other study areas in the Library were however within Categories III with less than 15% PPD (Table 3). This is considered as an acceptable level for existing buildings, which is 95% (May-June) and 97% (September-October) of the time during measurement period (Table 4). On average, occupants were less comfortable with PMV of -0.52 relating to a PPD of at least 10% (May-June). In contrast Phase 2 (September-October) the PMV value was almost neutral -0.02, that is a PPD of 5%. Therefore, the PPDs were both deemed to be within categories (I and II) suggesting that library users were mostly comfortable within both measurement periods.

Table 4 Recommended design categories

	PPD	PMV	Level of Expectation	*Percentage of time monitored in each category (%) May-June	September-October
I	< 6 %	-0.2 to +0.2	High	16	36
II	< 10 %	-0.5 to +0.5	Normal for new build	36	50
III	< 15 %	-0.7 to +0.7	Acceptable moderate level for existing buildings	43	11
IV	> 15 %	<-0.7or +0.7<	Only accepted for a limited part of the year	6	4

*Source: EN 15251 (2007) *Percentage for monitored area not including study pods*

3.2. Visual Comfort, Acoustic Comfort and Indoor Air Quality

Fig 2. Visual appearance of a UoR Study Pods

Table 5: Illuminance level

Location	Day			Night			Standards
	Min	**Max**	**Average**	**Min**	**Max**	**Average**	**Benchmark**
Computer Area	296	1530	**1,925**	289	319	**308**	**300**
Bookshelves	313	2267	**1,085**	134	317	**235**	**200**
Study Area	204	1652	**680**	201	526	**322**	**500**

The illuminance varied throughout the building, significantly the study area did not meet the benchmark requirements. The average illuminance level was within the range recommended by CIBSE for the computer room and bookshelves. Although the study area had the highest average illuminance than the other spaces, it was slightly below the standards by 178 lux (Table 5). It was observed that glazed areas had a significant effect on the measured lighting illuminance due to the penetration of daylight. This is reflected in the discrepancies between day and night illuminances with majority of day illuminances exceeding 1,000 lux in such areas. Based on visual inspection, artificial lighting was switched on 24-hour, suggesting a means of potential energy savings. This action would reduce the reliance of artificial lighting and hence, lighting loads without impacting the visual comfort. Other areas with similar day and night results were enclosed rooms with no windows or glazing, hence the need for artificial lighting. The noise levels measured during phase 1 which incidentally was the examination period exceeded the recommended range (of 25 - 35 dB) by 10 dB particularly in the group study open areas on the 2nd and 4th floors. Whereas the same study area was noted to be within the acceptable range during phase 2. On the other hand, the ground floor study area remains within the acceptable range not exceeding 35 dB for both measurement periods. The noise levels were therefore considered to be acceptable overall as it was predominantly between 25 to 35 dB as stipulated within CIBSE Guide A [13]. The calculated ventilation rate measured at the cellular office (0.25 ACH) was similar during phase 1 to that of phase 2. Values were slightly low in the study open area (0.18 ACH), suggesting an airtight façade. Majority of the time, the concentration of CO_2 did not exceed 800 ppm but there were some recorded peaks at 1,017 ppm in the cellular office and 1,391 ppm on the 4th floor group study area. These values were however within stipulated values documented by CIBSE [13], suggesting concentration levels to be within category IV.

3.3. Numerical Simulation

The breakdown of the energy consumption of the Library is as illustrated in Fig. 3. The trend of the simulated compared to the actual (Fig. 4) is similar with a 0.6% difference in projected annual energy consumption. It is not known what caused the difference (albeit small), however, with this accounted for in the model, the scenarios in Table 2 were modelled. From the simulated results, there were significant energy saving interventions from almost all scenarios but for scenario 5 and 6 where the building was simulated for NV at 1.5 ACH and 3 ACH. Although in scenario 5 and 6, indoor CO_2 concentrations were low, there was an increase in energy consumption (4.1% - 9.7%) and PPD (1.5% - 2.4%). The energy consumed and PPD increases as the number of air changes increases. Furthermore, scenario 1 and 3 shows decrease in energy consumption and PPD. The combination of scenarios 1 and 2 (scenario 3) offer a significant reduction in energy consumption as well as PPD. Lastly, the improvement of the HVAC system

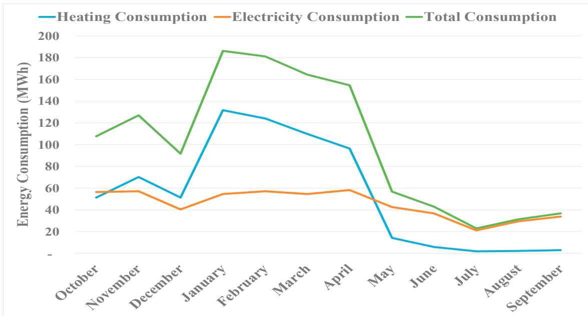

Fig 3. Actual breakdown of energy consumption

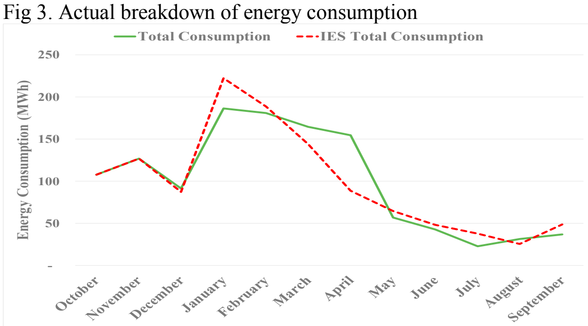

Fig 4. Actual vs Simulated energy consumption

(Scenario 4), offers the most reduction in energy consumption although it does not change the PPD levels. Despite these simulated variations, it is true that occupants are capable of adapting to the changing environment within the library at different times and seasons, however, this implies that a more flexible long-term design approach is required as the main solution to optimize the indoor environmental conditions.

Table 6. Simulation results of each scenario

	Scenario	Energy Consumption (MWh/yr)	Energy changes (%)	PPD (%)	PPD Changes (%)	CO_2 (ppm)
A	Existing	1,195.3		30.3		1,792
1	Glazing	1,001.5	-16.2	30.0	-0.3	1,792
2	Lighting	1,190.8	-0.37	35.9	+5.6	1,478
3	Glazing & Lighting	992.7	-16.9	29.5	-0.8	1,144
4	Efficiency (HVAC)	952.0	-20.4	30.3	0.0	1,792
5	NV 1.5 ACH	1,246.4	+4.1	31.8	+1.5	793
6	NV 3 ACH	1,311.5	+9.7	32.7	+2.4	616

4. Conclusion

This study presents results of an ongoing study that is designed to investigate measures required to ensure that good IEQ, comfort and energy efficiency are not seen as mutually exclusive. The study has demonstrated through experiments and modelling the impact of varied IEQ parameters on the IE. With the 24-hour operation of the UoR Library amidst varied occupancy numbers and activities, a complex phenomenon is presented. This stage of the research reveals the need for a flexible design approach to ensure IEQ parameters are optimized amidst energy saving design implementation. Further studies are ongoing regarding façade variation and its impact on adding to the elements that would only emphasis the parameters required to bridge the gap.

Acknowledgements

The authors would like to thank the University Energy team led by Mr Dan Fernbank, Mr Robin Hunter and the UoR Library staff for their selfless support.

References

[1] Gaspar PL and Santos AL. Embodied energy on refurbishment vs. demolition: A southern Europe case study. Energy and Buildings 2015; 386-394

[2] Carbon Trust. Building the future, today: Transorming the economic and carbon perfromance of the buildings we work in. Available at: http://www.ukgbc.org/sites/default/files/Carbon%20Trust%20-%20Building%20the%20Future%20Today.pdf

[3] Pout, C.H., Mackenzie, F., Bettle, R. (2002) BRE Carbon Emissions from Non-Domestic Buildings Available at: http://projects.bre.co.uk/PDF_files/CarbonEmissionsFromNon-domesticBldgs%202000andBeyond.pdf

[4] Akande OK, Odeleye D, Coday, A, JimenexBescos C. Performance evaluation of operational energy use in refurbishment, reuse, and conservation of heritage buildings for optimum sustainability. Frontiers of Architectural Research 2016;5:371-382

[5] Godoy-Shimizu D, Armitage P, Steemers K, Chenvidyakarn T. Using Display Energy Certificates to quantify energy consumption in the UK non-domestic building stock. CIBSE Technical Sympsoium 2013

[6] Mihai T, Iordache V. Determining the indoor environment quality for an educational building. Energy Procedia 2016; 85: 566-574

[7] CIBSE. Efficiency in further and higher education: Cost effective low energy buildings Energy Consumption Guide 54. Available at: http://www.cibse.org/getmedia/f944f3e0-e047-4c62-af85-43f02533f2de/ECG54-Energy-Use-in-Further-Higher-Education-Buildings.pdf

[8] Pistore L, Cappelletti F, Romagnoni P, Zonta A. Assessment of the IEQ in the two high schools by means of monitoring, surveys and dynamic simulation. Energy Procedia 2015;82:519-525

[9] Roulet CA. Indoor environment quality in buildings and its impact on outdoor enviornment. Energy and Buildings 2001;33:183-191

[10] Lawrence R, Keime C. Bridging the gap between energy and comfort: Post-occupancy evaluation of two higher-education buildings in Sheffield. Energy and Buildings 2016;130:651-666

[11] Ncube M, Riffat, S. Developing an indoor environment quality tool for assessment of mechanically ventilated office buildings in the UK – A preliminary study. Building and Environment 2012; 53; 26-33

[12] Lombard LP, Ortiz J, Pout C. A review on buildings energy consumption information. Energy and Buildings (2008);40:394-398

[13] CIBSE Guide A: Environmental design. 7th edition. Chartered Institutde of Building Services Engineers 2006

[14] British Standard Institute. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and coustics. BS EN 15251:2007