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On the comparison of occupancy in relation to energy consumption and indoor environmental quality: a case study

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Abstract

The present work focusses on the investigation of the correlation between occupancy, energy performance of the building as well as the quality of the indoor environment in terms of the thermal and air quality aspects. In this respect 3 different types of rooms (use and occupancy), situated in a building of the National University of Singapore campus, were selected. The building is equipped with an advanced BMS system capable of assessing the energy performance, the thermal behaviour and the air quality of all sections, thus providing guidelines towards a zero energy performance maintaining an acceptable indoor environment.
The results indicate that strong correlation between energy consumption and occupancy is identified while the levels of illuminance do not seem to be strongly influenced by the amount of people. The indoor concentration of CO_2 which is related to human exhalation, found to be high especially during the class hours. This is attributed to the insufficient performance of the mechanical ventilation central system which cannot be adjusted accordingly.

Keywords: occupancy, energy consumption, environmental quality

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1. Introduction

The energy performance of all dwellings and the quality of the indoor environment, has been the topic of research of many groups all over the world. This is of importance for many countries with tropical climatic conditions , where buildings account for over 36 % of the total electricity sales in the recent years and is expected to grow in the future [1]. The present research focuses on the case study of a typical building which operates in the campus of the National University of Singapore (hence forth NUS). Singapore Island experiences a warm and moist climate with rainfall rate averaging 2381 mm per annum. The diurnal variation of temperature is little and ranges by about 7 ^{0}C. At the same time the mean annual relative humidity is about 84% with typical daily maxima approaching saturation in the cooler early mornings [2]. This type of climate may have an adverse impact on occupant comfort [3]. Similarly, the occupants number alongside their environmental adaptation and activity in the building, their comfort and the energy consumption, is still subject of research. Recent research work has reported results on lighting, ventilation and air conditioning energy consumption in different climatic and cultural areas [4]. Both theoretical and experimental work indicates that for the Quebec and Rome climates, manual versus constant lighting control reduced lighting consumption by about 80% and that the cooling and primary energy loads are significantly reduced by 42% 57% ,60% and 43% respectively [5]. However the main source of energy consumption of a building is due to the spread of the HVAC (Heating Ventilation and Air Conditioning) installations which is further increased by the growing demand for better thermal comfort. In fact in developed countries HVAC is the main energy consumption system of a typical dwelling since it is responsible for almost half of the total energy consumption especially for the non-domestic cases, [6]. As far as the indoor environment is concerned, the increasing numbers of people in the building, results to higher levels of carbon dioxide (CO_2) produced mainly by human exhalation [7]. It is well understood that CO_2 concentrations can be used as a tracer gas for the evaluation of the ventilation system performance, [8 & 9].

The aim of this paper is to present the results of an experimental campaign that took place in an educational building of the National University of Singapore (NUS). The results refer to the energy consumption and air quality of three rooms, each one with different usage and occupancy. The impact of different occupancy patterns on the energy demands, the illuminance of the building, as well as the internal levels of temperature, relative humidity and CO_2, are examined. The study of these parameters, constitute an innovative contribution to the limited literature on energy consumption measurements within educational buildings of countries with hot and humid climate.

1.1. Methodology

The experimental campaign took place in 3 different types of rooms in terms of occupancy (an executive room, a computer room and a lecture theater) which were carefully selected from the block of buildings of the campus of the NUS. The main objective of the research was to investigate the impact of human presence to the change of energy consumption and indoor air quality within the building. In this respect, measurements were taken in situ on a continuous 24hour basis for a period of 4 months. During the experiment, the daily uses of every room (lectures, meetings, presentations etc.) and the operational details were also recorded. It is noted that the rooms are located in different floors and that the building is situated in the city center area.

Energy consumption (kWh), illuminance (lux), temperature (^{0}C), relative humidity (%) and CO_2 concentration (ppm) constitute the main measured parameters. Firstly, a raw database is created and analyzed qualitatively and quantitatively by statistical software tools. In order to achieve a high quality data acquisition, Tukey's Two Sided test [10] was implemented to remove unwanted outliers and replace them with missing values. Subsequently, with the aid of K- Nearest Neighbor (KNN) imputation technique [11] the missing data have been replaced by a weighted average of k nearest values. Thus, a smoother group of time series is achieved and unwanted measurements that could influence the final results are neglected.

The results should initially give a general view of the three rooms background for each measured parameter during the entire experimental period. Depending on this overview, the analysis focuses on specific days of interest where particularly high levels of specific parameters will be further analyzed so that the causes and conditions of this behaviour will be investigated. Moreover, the study of any potential correlation between variables will be facilitated so that final conclusions will be extracted. Finally, suggestions for possible solutions and improvements will be made where is deemed necessary.

2. Description of the case building

The building studied contains mainly offices, classrooms and a library space. The offices are open plan, accommodating a large number of staff and researchers. The library is utilised by students and contains a few permanent staff members. Windows in air conditioned spaces remain shut at all times during operating hours. The air conditioning system consists of multiple Air Handling Units (AHUs) and Fan Coil Units (FCUs), each serving separate areas. Some of the AHUs and FCUs are of the Single Coil Twin Fan System (SCTF), which decouples the fresh and recirculated air streams until they are mixed immediately prior to reaching the air conditioned zone. The fresh air stream is regulated according to ventilation and indoor air quality requirements, based on readings from CO_2 concentration sensors in the return air grilles, while the recirculated air stream is regulated according to the cooling load, based on readings from temperature sensors. The plant consists of three chillers, of which one is always on standby for extreme load conditions. Each chiller has its own dedicated set of pumps and cooling tower. Architectural plans, material properties, plant specifications and operating conditions were obtained from the building owner in the form of vendor documents, drawings and previous audit findings.

3. Description of the experimental procedure

Measurements were obtained by sensor kits, which contained four different types of sensors measuring CO_2 concentration, temperature, relative humidity and illuminance. Table 1 demonstrates the sensors used as well as their technical specifications. Energy consumption data (per minute) was obtained from the Building Management System (BMS). Occupancy per room was provided by observation of researchers and by the number of Wi-Fi connections.

Table 1. Technical specifications of the sensors.

Environmental parameter	**Sensor type**	**Range**
Temperature (°C)	Sensirion SHT75	-40 to 123.8 °C
RH (%)	Sensirion SHT75	0 to 100 %
CO_2 (ppm)	K-30, CO2 Meter Inc	0 to 5000 ppm
Illuminance (lux)	ROHM, B17xx	0 to 65000 lux

One sensor is placed in the executive office, two in the computer room and three in the lecture theater. Greater interest was shown in rooms with frequent fluctuation in occupancy such as the lecture theater and the computer room. Data is available at 1 minute sampling intervals.

4. Results

4.1 Investigation of energy consumption and indoor air quality

The main objective of this part of work is to investigate the indoor environmental quality and the energy consumption of three rooms. As a first step, it is of importance to study their energy and environmental behaviour.

Table 2, summarizes monthly values of the measured parameters for all three experimental sites thus allowing a total overview of the obtained results. Figures 1 and 2 show the total energy consumption and the total luminous emittance in the three types of rooms. It can be seen that the computer room and the lecture theater present the highest energy consumption as it is expected, since they are rooms with high occupancy rates but also with equipment (presentation equipment and computers). The executive room which is not used very often demonstrates low values of energy consumption and illuminance in most time as expected. Seasonality seems to be a key factor, since measurements during August and September presented extremely higher levels than the respective of October and November.

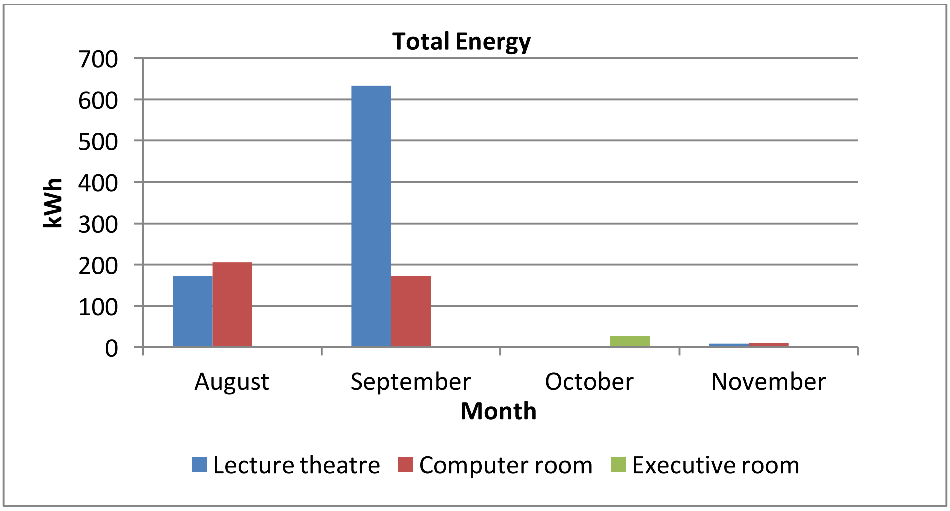

Figure 1. Total energy (excluding lighting) for the three rooms

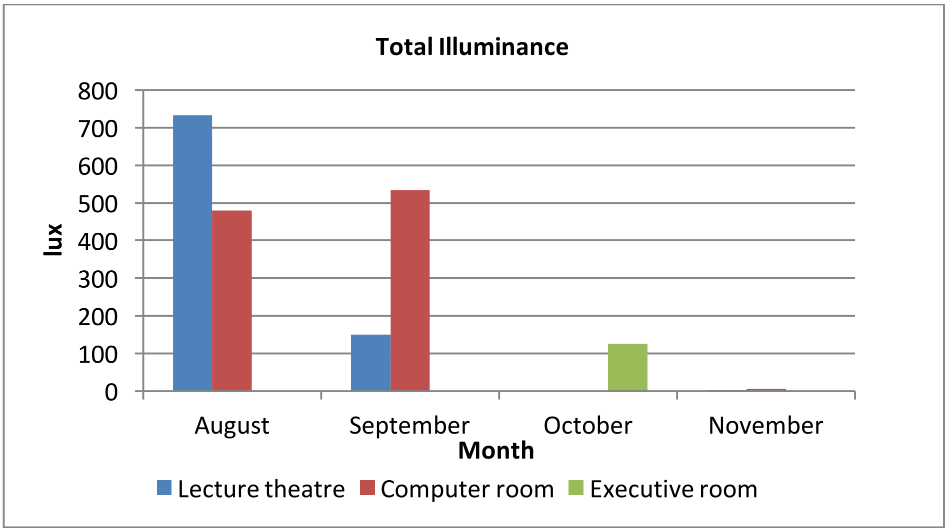

Figure 2. Total illuminance for the three rooms

The temperature and relative humidity measurements are illustrated in two different types of graphs. Firstly, in order to assess the overall thermal behaviour of the rooms, the box plot approach was used. Figure 3, presents the box plots of the (a) temperature and (b) relative humidity respectively. It can be seen that the lecture theater, which has the highest variability in terms of occupancy, shows the lowest mean temperature and the highest variation of temperature values. This is expected since the lecture theater is not always booked for lectures and even if it is, the number of people varies depending on the lecture topic.

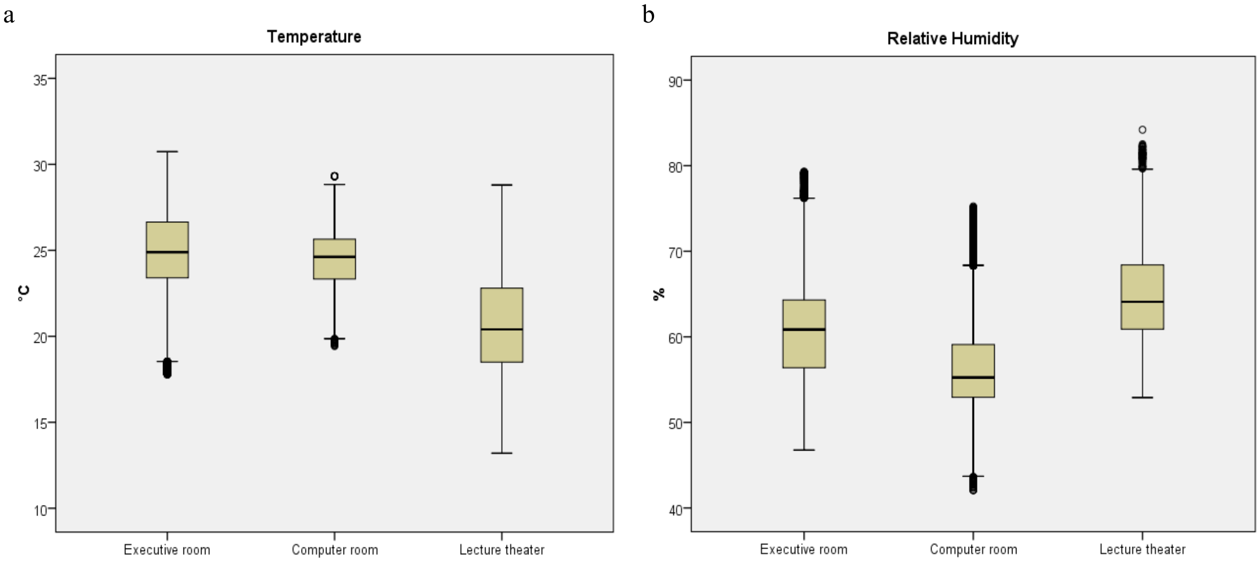

Figure 3. Box plots for (a) temperature and (b) relative humidity of the three rooms.

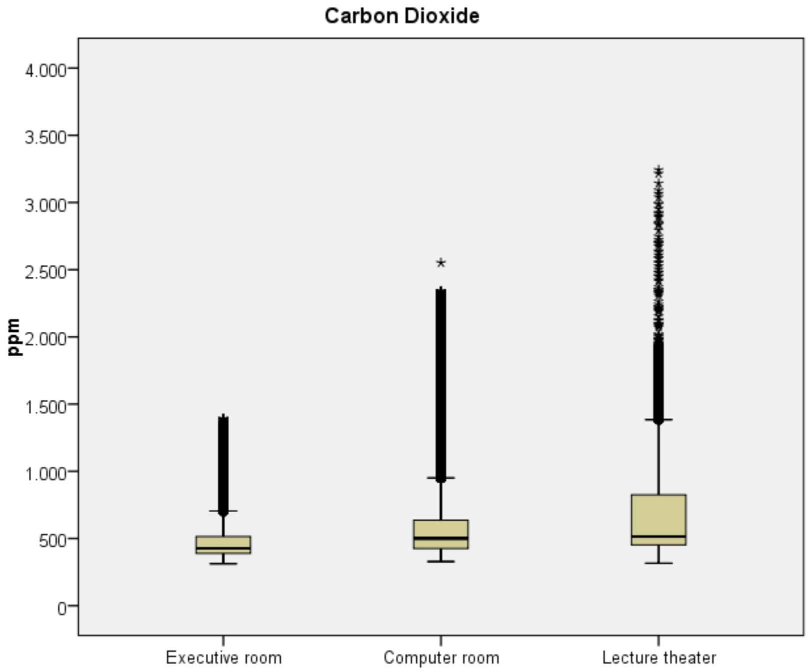

Figure 4. CO_2 concentrations in the three rooms.

Figure 4, shows the CO_2 concentrations in the three rooms. Once again, the lecture theater presents greater variability as a result of its varying occupancy patterns. From the above graphs, it is easy to conclude that the lecture theater presents the most interesting environmental behaviour due to the complexity of its occupancy patterns.

Table 2. Monthly values for all measured parameters within the three rooms.

	Year 2016				
Experimental sites	Parameters	August	September	October	November
Lecture Theater (sensor 70,5,13)	Total Illuminance [=lux]	732.5	150.3	0.0	3.0
	Total Energy [=kWh]	173.7	632.7	0.0	8.6
	Average Temperature [=^{0}C]	20.9	20.1	21.0	21.4
	Average Rel.Humididty [=%]	67.5	65.2	63.0	65.8
	Average CO_2 [=ppm]	817.0	635.7	705.0	543.5
Computer Room (sensor 50,37)	Total Illuminance [=lux]	480.6	535.0	0.0	4.9
	Total Energy [=kWh]	205.6	173.6	0.0	9.7
	Average Temperature [=^{0}C]	24.8	24.7	24.6	24.1
	Average Rel.Humididty [=%]	58.3	56.1	54.8	57
	Average CO_2 [=ppm]	554.2	559.3	655.8	523.6
Executive Room (sensor 20)	Total Illuminance [=lux]	0.0	0.0	126.1	0.0
	Total Energy [=kWh]	0.0	0.0	27.4	0.0
	Average Temperature [=^{0}C]	25.2	25	24.8	24.4
	Average Rel.Humididty [=%]	60.7	59.8	59.9	61.7
	Average CO_2 [=ppm]	454.1	464.9	513.7	472.6

4.2 Days of special interest

4.2.1 High occupancy

A specific day with high occupancy was chosen to show the daily variation of temperature, relative humidity and CO_2 concentration as well as the fluctuation of illuminance and energy consumption in accordance with the number of people in the lecture theater (figures 5, 6 and 7). Temperature and relative humidity are completely controlled by the air conditioning system and remain relatively stable. However, when a lecture starts (and during the course) and the theater is almost full, CO_2 is elevated in rather alarming levels (higher than the 1000 ppm ASHRAE limit). Moreover, temperature also rises but it does not exceed 25°C. As for energy consumption, it looks to be particularly influenced by the presence of people within the theater, as the peaks follow almost the same pattern of the respective occupancy. Illuminance does not seem to be strongly influenced by human presence. It is found to be elevated during the morning hours with a small amount of people inside and reduced in the early afternoon with much more occupancy during class. Thus, the levels of internal lightning seem to depend mainly from the openings of the room and the human activities (such as turning off the lights or using blinds or curtains) rather than from the amount of people inside. This conclusion is in agreement with the research of [12], who observed that there is a certain relationship but not a strict correlation between occupancy and (electrical) lighting operation.

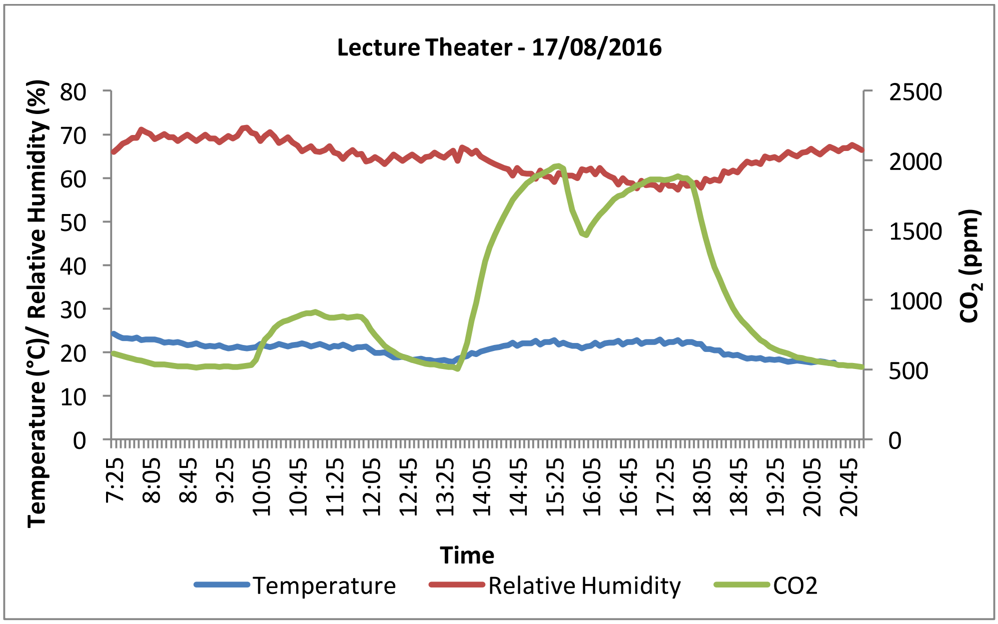

Figure 5. Lecture theater: one day with high occupancy.

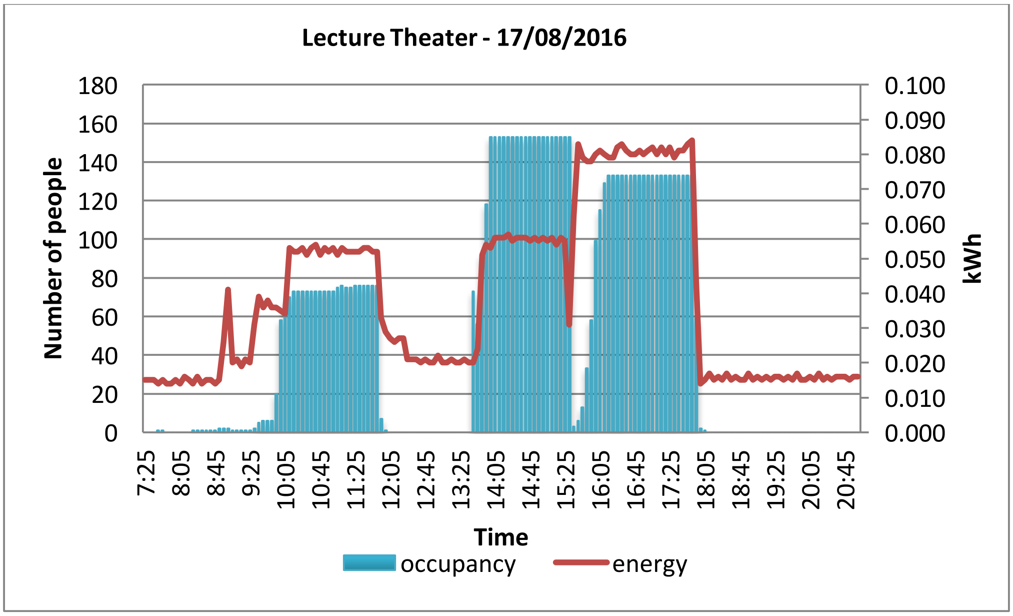

Figure 6. Energy consumption levels in lecture theater in respect with occupancy.

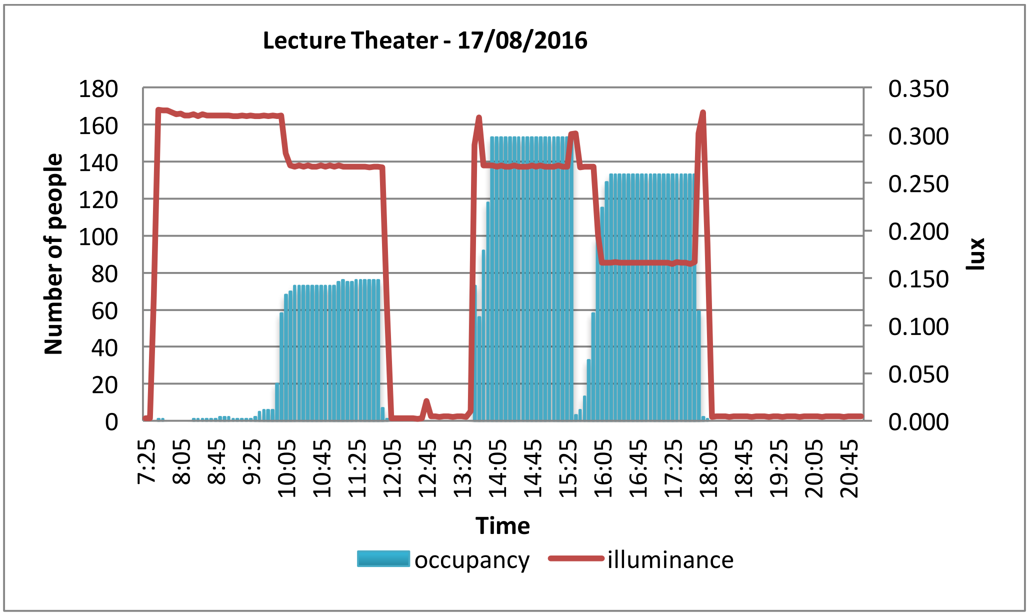

Figure 7. Illuminance levels in lecture theater in respect with occupancy.

4.2.2 Increased energy consumption

Another case study of interest is based on the analysis of a specific day of September when high levels of energy consumption were observed within the computer room. Figure 8, shows a correlation between energy consumption and the levels of CO_2 with a coefficient of determination (R^2) equal to 0.76. The result is statistically significant, as the p value of the ANOVA test approached zero. In this case, the concentration of CO_2 is used as an indicator of occupancy inside the room and demonstrates that the presence of people influences energy values mainly because of the electric load produced by the computers. The same result is observed in the experiment of [13] where the electricity consumption presented a significant positive correlation with the occupancy rate, even with a large proportion remaining constant over time. It is noted that temperature, relative humidity and illuminance remained stable in the room with no significant fluctuations.

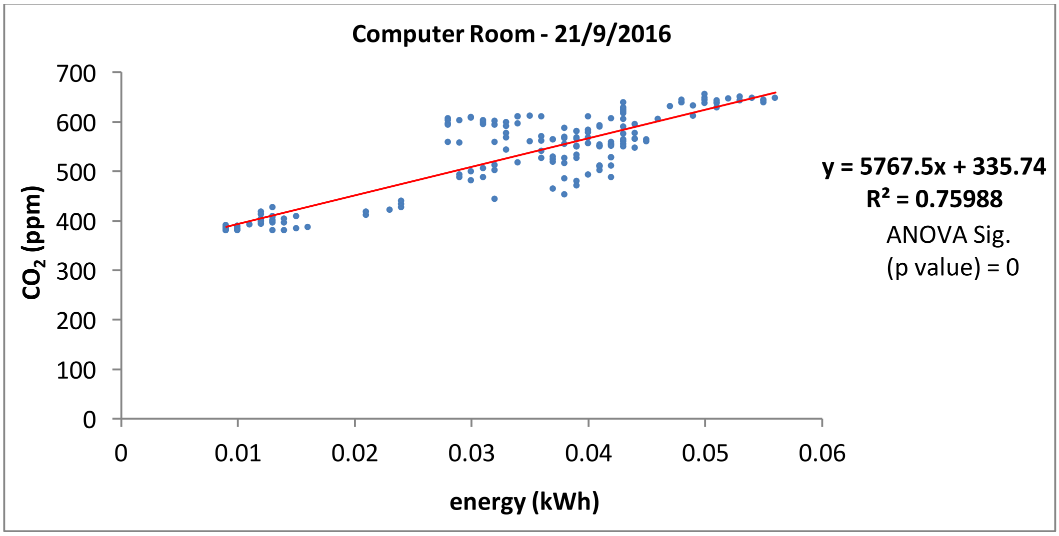

Figure 8. Scatter plot of CO_2 levels vs energy consumption for a specific day in the computer room.

5. Discussion and Concluding Remarks

The number of people and their activities within a building as well as its general structure (dwellings, offices, hospitals, educational institutions etc.) are the main factors influencing the energy consumption and the indoor air quality. A key question is whether the number of people affects each one of the examined variables and how the optimal use of the building is ensured, from the energy point of view. For that reason, three rooms with different characteristics, a lecture theater, an executive office and a computer room were selected as experimental sites.

The lecture theater presented a large variability for all parameters as it is not occupied frequently and high levels of energy demands in September are recorded. In the computer room, high values of illuminance were recorded during August and September. For the executive room, only for October low values of illuminance and energy consumption were measured.

It is clear that there is a strong correlation between energy consumption and occupancy. The levels of illuminance do not seem to be strongly influenced by the amount of people in each room but mainly from human activity. Indoor concentration of CO_2 which is related to human exhalation, found to be elevated during class hours while temperature and relative humidity remained relatively stable because of air conditioning.

The results can be summarized as follows:

- Occupancy is strongly correlated only with energy consumption and CO_2 concentrations.
- Illumination is mainly influenced by building's characteristics and human activities but not by occupancy levels. During a lecture, a large number of people may be in a relatively shady environment while under certain circumstances (exam periods or studying), a small amount of people may turn on all the lights.
- Because of the presence of a HVAC system, temperature and relative humidity remained unaffected by human presence and remains relatively stable for all three rooms.
- The room with the largest fluctuations of all variables was the lecture theater as it is used massively at regular time intervals, depending on the schedule.

Occupancy affects specific parameters (energy and CO_2) within an educational building of a hot and humid climate area. Since the number of people, which are using the specific section of the building, cannot be changed, smart occupancy sensors could be proved an appropriate solution. Similar research [14] indicates that these sensors can save up to 5% more energy. This can be proved useful for the present case of building.

Reduction of CO_2 levels can be achieved through the improvement of the operation conditions of the existing ventilation system (mechanical or natural). Specific research [15] can help towards this direction as it demonstrates predictive models of CO_2 levels for various types of buildings.

With respect to future work, further research can be conducted into two different directions. Firstly, as seasonality proved to play an important role in the final results, it is proposed to continue the experiments throughout an academic year in order to present a comprehensive annual behaviour of variables. Secondly, it would be of great interest to carry out similar measurements after the implementation of the proposed measures of improvement, in order to ascertain the percentage of energy savings in the building and the decreasing of CO_2 levels.

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References

[1] Q.J.Kwong, N.M.Adam, B. Sahari, Thermal comfort assessment and potential for energy efficiency enhancement in modern tropical buildings: a review, Energy and Buildings 68 2014.p.547–557.
[2] R.J. De Dear, K.G. Leow KG, S.C. Foo, Thermal comfort in the humid tropics: field experiments in air conditioned and naturally ventilated buildings in Singapore, Int J Biometeorol 34 (4) 1991.p.259-65.
[3] N.H. Wong, S.S. Khoo, Thermal comfort in classrooms in tropical, Energy and Buildings 35 2003. p.337–351.
[4] J. Langevin, J.Wen, P.L. Gurian, Quantifying the human-building interaction: Considering the active, adaptive occupant in building performance simulation, Energy and Buildings 117 2015.p.372–386.
[5] D. Bourgeois, C. Reinhart, I. Macdonald, Adding advanced behavioural models in whole building energy simulation: a study on the total energy impact of manual and automated lighting control, Energy and Buildings 38 2006. p.814–823.
[6] L Yang, H Yan, J.C. Lan, Thermal comfort and building energy consumption implications – a review, Appl. Energy 115 2014.p.164–73.
[7] V. Vasile, H. Petran, A. Dima, C. Petcu, Indoor air quality - a key element of the energy performance of the buildings, Energy Procedia 96 2016.p.277 – 284.
[8] O.A. Seppanen, W.J. Fisk, M.J. Mendell, Association of ventilation rates and CO_2 concentrations with health and other responses in commercial and industrial buildings, Indoor Air 9 1999.p.226–52.
[9] P.A. Scheff, V.K. Paulius, S.W. Huang and , L.M. Conroy, Indoor air quality in a middle school, Part I: use of CO_2 as a tracer for effective ventilation, Appl. Occup. Environ. Hyg, 15 2000.p.824–834.
[10] J. W. Tukey, One degree of freedom for non-additivity, Biometrics 5 1949.p.232-42.
[11] P. Keerin, W.Kurutach, T.Boongoen, Cluster-based KNN missing value imputation for DNA microarray data. IEEE International conference on systems, man, and cybernetics (SMC), 2012.p.445–450.
[12] A. Mahdavi, A. Mohammadi, E. Kabir, L. Lambeva, Occupants' operation of lighting and shading systems in office buildings, Journal of Building Performance Simulation, 1 (1) 2008.p.57–65.
[13] A. G., Hestnes & N. U. Kofoed, Effective retrofitting scenarios for energy efficiency and comfort, results of the design and evaluation activities within the OFFICE project, Building and Environment, 37 2002.p.569–574.
[14] V. Garg and N.K. Bansal, Smart occupancy sensors to reduce energy consumption, Energy and Buildings, 32 2000.p. 81–87
[15] A. Pantazaras, S.E. Lee, M. Santamouris, J. Yang, Predicting the CO_2 levels in 400 buildings using deterministic and identified models, Energy Build., 127 2016.p.774– 785.