Optimizing Indoor Environmental Quality in hot arid climates

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Abstract. Indoor Environmental Quality (IEQ) is a key indicator of the quality of the built environment and the health of its occupants. The purpose of this study is to investigate a range of IEQ parameters in buildings located in hot, arid climates, representing some of the recurring challenges in offices. The study aims to identify the main IEQ factors and their acceptable ranges, including light, thermal comfort, air quality and noise. An IEQ index is utilized (Wagdi et al. 2017) as a tool which assesses the predefined IEQ parameters in office buildings providing a rating scheme which aggregates the obtained readings. Data collected from offices located in Dubai and Cairo is used to assess the indoor environment against defined benchmarks. The full range of parameters was monitored in a group of office spaces and the obtained readings were used to compute the IEQ index. For this investigation, all offices were completely fit out and tests were performed after at least one month of operation. The recorded results demonstrate that with careful design and informed material selection, acceptable IEQ levels can be achieved. The results and application of the index aim to provide an assessment tool to optimize design and construction practices, ultimately improving employee productivity, comfort and health.

Keywords. Indoor Environmental Quality, offices, VOC, light levels, arid climate.

1. Introduction
The indoor environment is highly impacted by the building design and construction, through several factors including building orientation, glazing ratio, ventilation systems and materials. Occupants are affected by the exposure to these elements collectively. Previous studies have assessed occupants’ comfort through conducting Post Occupancy Evaluations (POE) in the form of surveys in order to learn more about the factors having the highest impact on user satisfaction, and to suggest solutions to enhance the indoor environment. In some cases, POEs are accompanied with more objective assessment methods which entail quantitative analysis of a single factor or multiple factors of Indoor Environmental Quality (IEQ). As new building rating systems emerge with an increased focus on improving health and wellbeing indoors, the measurement methods and assessment tools are optimised and the benchmarks become more standardised. This paper aims to assess the indoor environment through a quantitative analysis of the measured IEQ parameters in a number of office buildings. This shall identify common observations due to the hot, arid climatic condition.

1.1. Background and Literature Review
Several studies have been conducted in residential and office buildings to evaluate IEQ parameters. However, previous studies were more common in countries with cooler climates. The studies ranged from those testing indoor air quality only [1] to others which considered multiple IEQ parameters [2-5]. In the MENA region, where countries have a hot, humid and arid climate, there are a limited number of studies addressing health and wellbeing in the built environment. Hot, arid climates and the reliance on mechanical ventilation can trigger irritation and inflammation of the airways with increased heat and humidity [10]. Existing studies may address one or two parameters such as air quality or light levels
only, and tend not to cover a comprehensive evaluation of the combined effect of the full range of parameters building occupants are exposed to. Previous studies have assessed some parameters through either pre-occupancy or post-occupancy assessments [6-9]. The benefits of improved IEQ in office buildings has been proven through recent studies, such as the one conducted by Saint Gobain demonstrating that, with a 90% improvement in Indoor Air Quality (IAQ) and 40% improvement in acoustical comfort, approximately 40% of employees reported feeling more productive and 53.7% reported an improvement in perceptions of health and wellbeing [11]. In another study, it was recorded that an average of 3.5 fewer workdays due to sickness were missed in Skansa’s remodelled office in Northern Hub, Doncaster, as compared to their other offices in the UK. This saved the company approximately USD 37,500 in staff costs in 2015 as well as improving employee satisfaction by 20% [12].

1.1.1. Impact of Hot, Arid Climates and Responsive Design. Studies conducted by de Dear and Fountain in hot, humid environments demonstrated that building occupants were generally less tolerant of thermal comfort conditions ranging outside of the prescribed comfort zone. A preference was also noted for air movement, as opposed to ‘stagnant’ air conditions. This study identified the need to differentiate between climate conditions when setting internal design criteria, with significant differences in preferences and comfort criteria resulting from the acclimatization of populations to external conditions [13]. When considering the physical built environment, several factors affect a building occupants health. These include air and water quality; thermal comfort; lighting and noise. With many urban environments presenting challenging conditions for most of these elements, with consideration to air pollution, limited access to natural light and typical noise levels, hot and arid climates present additional challenges when designing buildings in order to overcome heat stress conditions and manage humidity levels. Active design for health and well-being supplements passive design measures when critical conditions are reached. There is an increase in reliance on active design features include Heating, Ventilation and Air Conditioning (HVAC) systems to provide mechanically cooled and filtered fresh air, and electronic lighting where natural lighting conditions are insufficient for the intended building function.

1.1.2. Literature Review – Previous Studies Conducted and Results. A case study presented by Morhayim and Meir assesses the satisfaction of occupants in a pre-determined “unhealthy building” through a POE survey. The results demonstrate dissatisfaction relating to air quality, with symptoms ranging from headaches and fatigue to eye irritation, dry skin and sore throats. Measurements taken highlight low internal humidity levels of 20%, considered as a main contributor towards eye irritation, dry skin and sore throat symptoms, as well as a poorly designed and maintained HVAC system and predominantly south facing windows, resulting in low air quality and glare issues causing headaches and fatigue. Due to the hot and arid region of the study, there is a presumption that building’s must be airtight and air-conditioned. The authors challenge this preconceived notion and argue the case for passive design measures to be considered, reducing the reliance on active cooling systems through partially naturally ventilated buildings [14].

Another study conducted by Fadey, Alkhaja, Sulayem and Abu-Hijleh within a school classroom in the United Arab Emirates (UAE) assessed the (IAQ), thermal comfort, lighting and noise quality. The results of the study demonstrated poor air quality, with high levels of TVOC, CO2 and Particulate Matter (PM). The ventilation for the classrooms relied heavily on infiltration, meaning that insufficient, direct, clean fresh air supply was not being provided in order to meet acceptable conditions. Average temperature levels, of 24.5°C, were found to be within the upper 35th percentile of considered acceptable conditions, with several classrooms exceeding the recommended temperature limit of 25°C. The lack of solar shading devices along with a leaky building envelope were identified as potential causes for thermal discomfort. The gaps in the building façade, along with poor internal acoustic treatment, also resulted in high average sound levels of 59dB, exceeding recommended levels of 35dB. Natural daylight was observed to be inhibited in many spaces due to the need for internal blinds to mitigate glare. External
shading devices could be used to enhance daylight ingress while reducing glare and the subsequent need for internal blinds [15].

2. IEQ Measurement and Analysis

2.1. Methodology

The proposed methodology allows the classification of the IEQ parameters within each category as well as the aggregation of multiple categories into a single index to rate the indoor environment. The first stage of the study includes the identification of relevant parameters in an office setting. This is followed by the identification of acceptable limits for each of the parameters. The second step was to collect measurements from different locations and to analyse these reading against the identified limits. Finally, the index was designed to provide an assessment of the overall environment.

2.1.1. Case Study Description and Data Collection. Data was collected from four office locations as shown in the table below. Two of these offices are in DIFC, Dubai and one is in the on the Sheikh Zayed Road, opposite to Business Bay which are all within medium density urban districts. Each of the studied locations includes open workspace, closed offices, meeting rooms and one or more breakout space(s). The fourth location was in New Cairo, Egypt, in a university campus where enclosed administration and faculty offices were tested. Measurements were recorded following the same methodology across each of the offices. Lux levels were measured at the surface of the workstation, where at least three measurements were taken for each task/application in each office location. Air samples were collected at a height of 1.1-1.7m (breathing zone) and it was ensured that the sampling points are 1m away from walls, doors, windows and air exhaust outlets. For projects with multiple floors, measurements were distributed across different floors including the highest and lowest regularly occupied floors. Both real time data loggers as well as active samplers were used for the air quality parameters in accordance to the WELL Performance Verification Guidebook [16]. Thermal comfort data was also recorded during the time of testing. Sound measurements were performed when the spaces were unoccupied and were taken at a minimum of 1.2m above finished floor level. Sound levels were measured with the HVAC system turned on and off to test for exterior as well as interior noise intrusion.

The measurements were taken between the years 2018-2019, during different times of the year. However, the cooling system has been operating throughout the studies regardless of the season. Several IEQ parameters were monitored in each of these locations including ambient lux levels, air quality (formaldehyde, TVOCs, carbon monoxide, ozone, PM2.5 & PM10), thermal comfort (temperature & relative humidity) and noise levels. All testing has been done under the project’s regular conditions and no alterations have been made to the HVAC settings or space layout.

Table 1. Project Data

| Project Number | 1          | 2          | 3          | 4          |
|----------------|------------|------------|------------|------------|
| Location       | Sheikh Zayed Rd, Dubai | WTC, Dubai | DIFC, Dubai | New Cairo, Egypt |
| Number of floors | 1          | 1          | 5          | 1          |
| Area sqm       | 227        | 1,892      | 4,782      | 80         |
| Fit out Completion | 2017      | 2017      | 2013      | 2009       |
| Building Construction Completion | >10 years | <2 years | >15 years | >10 years |
| Ventilation System | Centralized, ducted system and natural ventilation | Centralized, ducted system | Centralized, ducted system | Centralized, ducted system |
2.2. Index. The method followed to compute the IAQ index by the authors [9] was revised to include the IEQ parameters listed in this study. The weights for each parameter were recalculated following the Analytical Hierarchy Process (AHP) and the recorded readings were used to calculate the index for each of the tested locations. Where the recorded value meets the recommended benchmark a score of 0.5 was provided, whereas readings which are acceptable were given a score of 0 and not acceptable readings were given a score of 1. The total score is then multiplied by the weight.

3. Results and Discussion

3.1. Final Results

3.1.1. Light Levels. The light levels were measured to ensure that the interior electric lighting provides an average light intensity of 215 lux or more. Additionally, the lighting in the individual spaces was checked against the illuminance threshold specified in IES Lighting Handbook 10th Edition.

Office 1 & 2: The lux levels have exceeded 200 lux in all spaces including offices, open workstations, reception desk as well as the meeting rooms.

Office 3: Recorded lighting levels in multiple locations such as meeting rooms, video conference rooms were lower than the recommended limits. It was evident that workstations are generally well illuminated, meeting the minimum requirements and in many cases a task light is also provided. Reception desks and meeting rooms, where tasks required less writing and typing have been designed with lower lux levels and in some cases located away from the window which reduced interference from outdoor sources thus lower readings were recorded.

Office 4: Lux levels were recorded under the effect of artificial lighting as well as daylighting separately. Lighting levels were acceptable in all offices with the exception of one, where it is evident that both electrical and natural daylight did not meet the required lux levels in the space. The reason for this was that the office layout and proportion required a higher density of artificial lighting and/or a larger window area.

3.1.2. Air Quality. Each of the measured parameters were studied and analysed separately, based on which the factors that contributed to poor air quality were proposed.

Office 1: The formaldehyde levels were high within the first year after completion of fit out work. It is expected that the installed materials have contributed to the increase in formaldehyde levels. After approximately two years of the completion of construction, and with the introduction of plants, formaldehyde levels dropped to 34 and 39 ppb (measured in two locations inside the office space). Recorded Total VOCs were higher that the specified limit of 500 µg/m³. However, the individual VOCs were all meeting the acceptable limits. The particulate matter (PM) levels were acceptable with PM 2.5 being significantly below the limit while PM 10 was borderline.

Office 2: Formaldehyde and VOC levels were measured within the first year after completion of fit out work and the readings were acceptable. PM 2.5 levels were acceptable while PM 10 have exceeded the limit in one of the locations due to ongoing construction and fit out work within close proximity from the site location.

Office 3: Fit out work was completed 5 years prior to testing showed significantly low levels of formaldehyde content. Although there is not enough data about the procured furniture, it is unlikely that the furniture and furnishings installed have low formaldehyde content.

Office 4: Many of the recorded air quality parameters were exceeding the recommended limits in this location. The formaldehyde and VOC levels were significantly high compared to all other offices which is expected to be resulting from the large amount of wooden furniture in the space. Carbon monoxide and ozone were quite low. Both PM 2.5 and PM 10 were either borderline or exceeding the
limit. This may have resulted from the reliance on natural ventilation in these offices as well as the HVAC filters being of a low rating compared to offices 1, 2 & 3.

3.1.3. Thermal Comfort. It is recommended that the temperature and relative humidity levels indoors are (22.5 to 25.5°C) and (30-60%), respectively. The recorded temperature in all locations was within the recommended range, except for three floors in office 3 where temperature settings were below the recommended level (too cool). Relative humidity levels were acceptable in all locations except for one floor in office 3. The increase in RH levels may be due to several elements including FAHU, damper, sealing of facades or exhaust air ducts.

![Formaldehyde](image1.png)  ![VOCs](image2.png)  ![Particulate Matter (PM2.5 & PM10)](image3.png)  ![Temperature & Relative Humidity](image4.png)

**Figure 1.** Recorded readings

3.1.4. Noise Levels. The sound pressure levels in all occupied spaces were measured recording the outside noise intrusion and internally generated noise due to mechanical systems. All offices have met the specified noise levels with the current design considerations except for office 4 which has exceeded the benchmark marginally.

Finally, the index score was calculated for each test location in the four offices. These values are presented in the table below, indicating 1 for acceptable, 2 for space needs improvement, 3 for poor and 4 for unacceptable. Based on the index results, project 4 which is not seeking green building certification shows that most test locations need improvement. Projects 3 also needs improvement in some of the test locations while projects 1 and 2 were the best performing.

| Location Number | 1-1 | 1-2 | 2-1 | 2-2 | 3-1 | 3-2 | 3-3 | 3-4 | 3-5 | 4-1 | 4-2 | 4-3 | 4-4 |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| IEQ Index       | 1   | 1   | 1   | 1   | 2   | 1   | 1   | 1   | 1   | 2   | 2   | 2   | 1   |

**Table 2.** IEQ Index Results
3.2. Recommendations

Based on the recorded readings and observations, recommendations were provided to ensure that all parameters are within acceptable limits. Additional lighting was requested or the existing fixtures in dark sports shall be replaced to meet the recommended lux levels. With regards to air quality, it is evident that the time after construction or fit out work, building operations and installed materials can all affect the Indoor Air Quality. Other possible reasons for the increase in VOC and formaldehyde content would be occupants’ activities as well as certain types of cleaning products. It was evident that cleaning products such as bleach may have contributed to higher levels of carbon tetrachloride (a type of VOC). Both the ozone and carbon monoxide were below the acceptable limit in all offices. Where all procured materials were reviewed for acceptable levels of formaldehyde content prior to installation the air quality was observed to be acceptable. It is therefore highly recommended to ensure that all finishing materials and furnishings are checked for low VOC and formaldehyde content. A flush out should be conducted upon completion of construction and enough time between fit out and occupancy can also have a positive influence. Opting for green building certifications such as LEED where fresh air calculations and HVAC systems are reviewed in accordance to ASHRAE Standard 62.1, has shown to contribute positively to IAQ. To ensure that formaldehyde is maintained at an acceptable level (below benchmark), informed decision-making during procurement of all materials and cleaning products, sufficient fresh air and ventilation, introducing carbon filters and certain types of plants can be considered. The facades are expected to be one of the contributors to poor acoustic performance in office 4, since the windows are wooden framed, single glazed and operable compared to aluminium framed windows in office 1 and non-operable windows in offices 2 & 3. Therefore, the selection of glazing, window frames to ensure that air infiltration is kept to an acceptable level, is also important. The designed index has been based on an office environment, taking into consideration the factors that are most likely impacting the productivity of staff. It was evident through the index that buildings that do not target green building certification have recorded the lowest scores in terms of IEQ levels and vice versa. In future work, the index can be enhanced taking into consideration different space typologies within a building. The index can also be reformed based on the building type and occupants’ vulnerability to certain parameters as well as their health conditions.

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