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THE DEVELOPMENT OF AN INDOOR ENVIRONMENTAL MONITORING FRAMEWORK FOR POST-OCCUPANCY EVALUATION USING REAL-TIME WEB-TOOLS

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ABSTRACT

The Arup Boston Office has recently relocated to a new space in which it has reinforced workplace wellness and has been awarded both WELL and Fitwel certifications. In order to evaluate the impact of wellness strategies implemented, a Post-Occupancy Evaluation (POE) was conducted that utilized an in-house designed sensor kit that records environmental parameters including dry bulb temperature (C), relative humidity (%), horizontal illumination level (lux), carbon dioxide (CO_2) concentration (ppm), particulate matter (PM $_{1,\ 2.5,10}$) and VOCs (Volatile Organic Compounds).

This research highlights an emerging POE framework that draws on both quantitative (sensor readings) and qualitative (occupant surveys) data sources while utilizing a real-time web dashboard that displays sensor readings internally to the Arup network. The novelty of this research lies in streamlining data access and analysis for ease of replicability while gaining insight into best practices for POE.

INTRODUCTION

Post Ocupancy Evaluation has been widely used in the building industry to assess the performance of indoor environments. It can be defined as the "the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time" (Preiser et al., 1988). The discourse has seen research that spans the use of indoor sensors, occupant surveys and various tools to collect both quantitative and qualitative data that can provide an insight into the performance of spaces.

Americans, on average, spend approximately 90 percent of their time indoors (US EPA, 11989). With regards to office design, the focus on health and employee well-being has been gaining a lot of attention. Studies have shown that there are direct correlations between employee productivity and the office environment they occupy. A study carried out at the Harvard Public School of Health looked at the cognitive performance of employees in green buildings across nine different function domains including crisis response, strategy and information usage. It was found that cognitive performance scores for the participants who worked in the green environments were, on average, 61% higher than those who worked in conventional environments.

As such, frameworks have been developed to address a new generation of building assessment tools that meet the current and forthcoming requirements associated with a building's contribution to sustainable development (Lutzkendorf and Lorenz, 2006). These frameworks have utilized IEQ (Indoor Environmental Quality) assessments but have also targeted building occupant satisfaction feedback.

The emergence of the concepts of big data and IoT (Internet of Things) have enabled building assessments to adopt advanced processing power through cloud computing and real time feedback. Post occupancy evaluations are relying on more and more complex models using both real-time and historical data (Linder et al, 2017). This provides an unprecedneted insight into streams of building data and ultimately information that can help us enhance the environments we occupy.

While many POE methods have placed building diagnostics and anomoly detection (Burton et al., 2014) at their core, this study aims to gain value from comparative performance across the two offices as well as increased awarness and understanding of the correlations between building strategies and employee satisfaction (cause and effect). The final goal is to develop a tool and visualisation technique that would facilitate the replicability of such analysis.

Relocating the Arup Boston office provided an opportunity to assess the spatial attributes that enhance office building design and employee wellness. This is especially true to the strategies surrounding lighting and circadian rythyms. Our sensing methodology was used to predict compliance with the lighting feature in WELL and was in line with the Performance verification results. This is discussed in more depth in the lighting section.

The study outlined in this paper intends to accomplish the following:

1. Assess and compare the performance of the two office spaces with reference to quantitative

environmental parameters in addition to employee perspectives through an occupant survey.

2. Analyze IEQ data for compliance with standards and identify any area of poor performance
3. Develop a real-time web-tool that facilitates the extraction and visualization of sensor data

METHODOLOGY

As noted previously, the framework developed utilizes a sensor kit, an occupant survey as well as a web dashboard to view results. The below diagram summarizes the methodology.

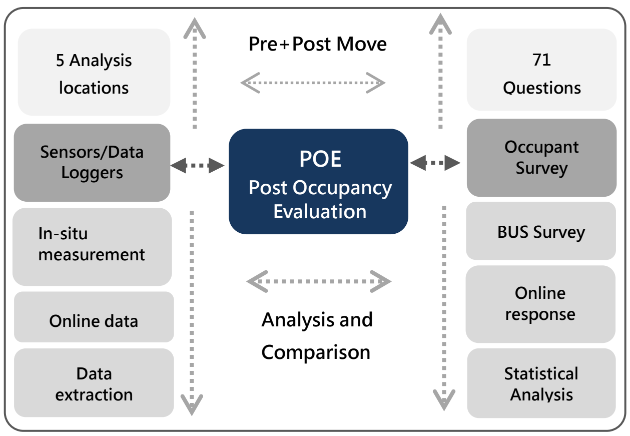


Figure 1 Framework of Analysis

The sensor kit

The senor kit utilized in the study was designed, assembled and programmed in-house. The London Building Performance and Systems team at Arup led this effort and assisted in feeding the live data from the sensor to the web-dashboard. The sensor stack (collection of combined sensors sharing a common electronic array) was housed inside a 3-D printed case (mounted on a tripod) to protect the connections and wiring that did not need to be exposed to the external environment.

The individual sensors (bricklets) were manufactured by Tinkerforge (https://www.tinkerforge.com/en/). Individual brickelets measured the following parameters: dry bulb temperature (C), relative humidity (%), horizontal illumination level (lux), carbon dioxide (CO_2) concentration (ppm) and particulate matter (PM 1, 2.5,10) and VOCs (Volatile Organic Compounds). In order to ensure accurate data, the PM and CO_2 sensors were cleaned regularly. In addition to this, the lighting senor was calibrated against an external light meter.

Figure 2 Photograph of Sensor kit

Web Data Interface- User Dashboard

The aim of the web- interface was two-fold; to facilitate the ease of data extraction for post processing as well as enhanced graphical visualization that would allow employees to access the data with ease. The sensors come with a software (Brick viewer) that can be used to program in python the logging intervals and download the data through a usb- connection. In order to streamline this process, a web-live data dashboard was set up to view the readings from all sensors. The data updated at one minute intervals and relied on the connection to the Arup Network (through ethernet cable). The sensor information is sent to an open source database that is running on an Arup server in London. To achieve data visualisation, our programmers utilized an existing open platform for analytics and monitoring as well as visualization- Grafana. A script was set up within brick viewer to communicate the data from the sensors to the dashboard. This sequence is shown below.

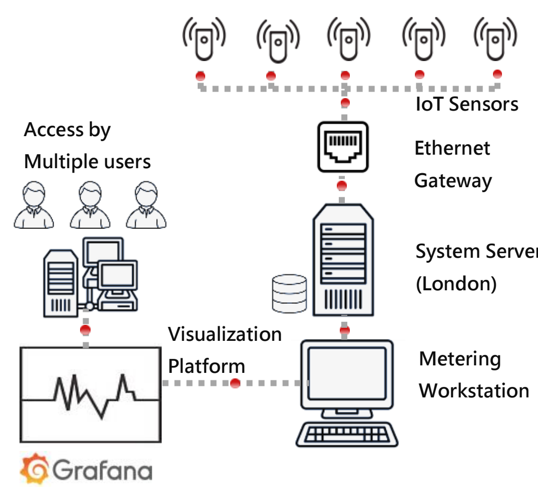


Figure 3 Online Tool Architecture

Data Post Processing

The live data validated that the sensors were recording and well calibrated. For the purpose of this study, statistical variations needed to be plotted and compared across the Indoor Environmental Quality categories of Air, Temperature Humidity and Light. As such a script was set up in R- a software for statistical computing and graphics. This custom script computed the data collected in the form of box plots to represent the median values as well as quartile distribution to give an insight into spatial performance. The results represented show data during occupied hours (8am-6pm). The plots are presented in the results section.

EXPERIMENT SET-UP

Spatial Monitoring Schedule

The study aimed to understand the environmental differences that exist between the two offices as well as across different space types. As such each office had a total of five different monitoring locations. At each location, the sensor kit was kept for 3 full days (72 hours). It was ensured that these days were full working days-weekends and holidays were not included. The spaces analyzed were as follows; the kitchen, meeting room (not façade facing) and three work Areas. The specific spatial set up was standardized across the 2 offices as much as possible- ie. distance from windows, proximity to workstations. All readings were taken in winter- December- January. At the time of the study, the office housed 82 employees.

Occupant Surveys

The surveys were distributed to the users in both the old and new office space and had a total of 70 questions.

The survey drew on questions and modules developed for the BUS (Building Use Studies) survey, for which Arup is a partner. The same survey was distributed in both offices and targeted satisfaction with office environmental quality as well as mind and comfort related questions.

RESULTS

The table below provides a reference for compliance with the recommended environmental thresholds under each category (Air, Humidity, Temperature and Light)- these values are also marked on the graphs.

The data presented below shows both the findings recorded from the sensor as well as the occupant surveys. For additional context, the associated environmental features implemented are also highlighted.

PARAMETER	RECOMMENDED RANGE	REFERENCE
Temperature	67- 78 F	ASHRAE 55
Light (lux)	Meeting Room: 215	IESNA
	Work stations: 300	
	Breakout: 100-300	
Pm 2.5	15 µg/m3	US EPA
Pm 10	50 µg/m3	WHO
Humidity (%)	40-70	US EPA
CO (ppm)	800 ppm (max) in densely occupied	WELL/Illinois Department of Public
VOCs	500 µg/m3	LEED

Table 1 Assessment Standards and References

Air

Strategies implemented in new office*:*

The ventilation system was designed to optimize air quality through filtration and provide fresh outdoor air. Low VOC interior finishes and furnishing were selected to eliminate the presence of harmful contaminants in the air.

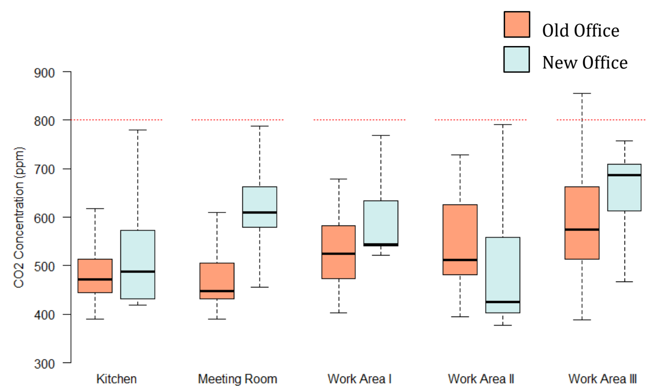


Figure 4: CO2 Measurements

Sensor Results:

Very low to negligible levels of VOCs and PMs were recorded in both offices (PM data is not shown as readings were well below recommended thresholds). CO_2 levels stayed below 800pm in both offices. Higher CO_2 levels recorded in new office than the old office at work areas, meeting room and kitchen. Work Area III room in new office shows highest recorded CO2 levels with a median of 700 ppm.

Occupant Survey results:

72% of staff said they were satisfied with the air quality, as compared to 13% in our old office.

Humidity

Strategies implemented in new office:

Mechanical system design to handle both latent and sensible space loads.

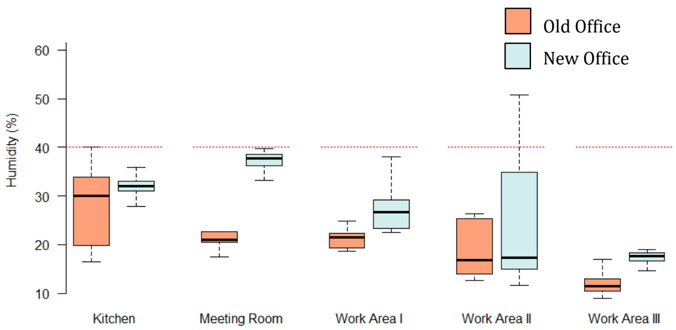


Figure 5: Humidity Measurements

Sensor Results:

Humidity levels in both offices was below 40%. This can be attributed to dryer winter weather. With the exception of Work Area II in the new office, humidity levels do not show high fluctuation. Humidity levels were higher in the new office than the old office. The Meeting room in the new office shows highest recorded humidity levels with a median of 37%

Occupant Survey results:

38% of staff said they were thermally comfortable in the new office, compared to 15% in our old office.

Temperature

Strategies implemented in new office:

The use of series type fan powered terminal units reduces the need for operation during unoccupied hours- this is an energy efficiency strategy

The system responds to the ventilation needs according to occupancy levels.

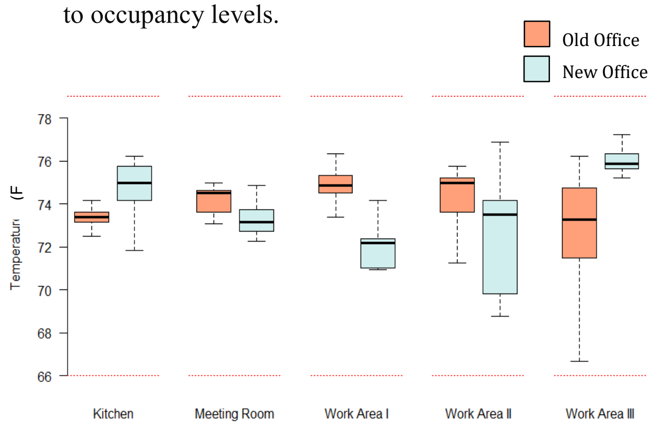


Figure 6: Temperature Measurements

Sensor Results:

Temperatures in both offices were within the comfort range of 67- 78 F. With the exception of Work Area II in the new office, large temperature fluctuations are not present in the data set. Work Area III in the new office shows highest recorded temperature levels with a median of 76F

Occupant Survey results:

38% of staff said they were thermally comfortable, compared to 15% in our old office.

Light

Strategies implemented in new office:

Tunable lighting controls are installed in the new office. There is greater access to daylight with the larger windows. A lighting power density of 0.67w/sqft was used- this reduced lighting energy usage. A circadian lighting system that mimics the natural cycle of daylight (changes color temperature throughout the day) and provides sufficient lighting levels at workstations was installed.

Figure 7: Light Measurements

Sensor Results:

The lighting level in old office was below 300 lux with the exception of the kitchen area since the monitoring location was façade oriented. Higher lighting levels measured at new office. The meeting room and Kitchen spaces show higher fluctuation in lighting levels throughout the day- due to impact of daylight

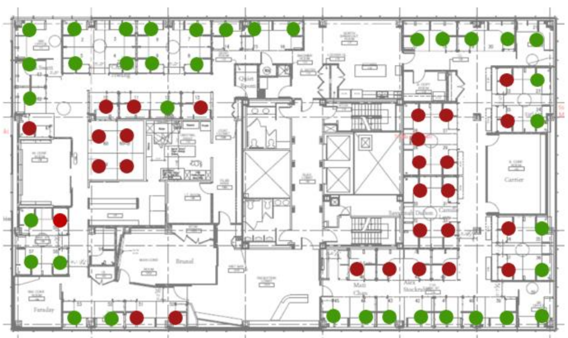
Occupant Survey results:

75% of staff agree that the lighting environment is comfortable, compared to 42% in our old office.

81% of staff are satisfied with glare levels at their workstations, compared to 51% in the old office.

In addition to lux measurements, a spectrum meter was used to measure EML (Equivalent Melanopic Lux) levels at workstations. These readings factor in light color temperature as well lighting level.

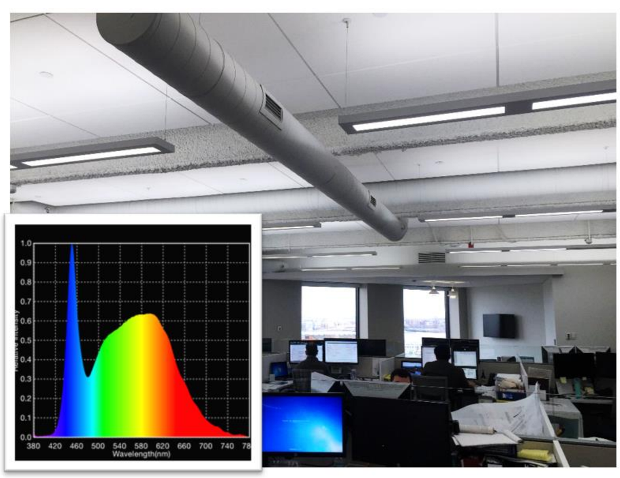
The results show compliance with the 200 EML requirement specified by the WELL building Standard for 75% of workstations in our new office, compared to 54% in our old office. Results and photographs of both spaces are shown below. These measurements were all taken between 9am and 1pm.



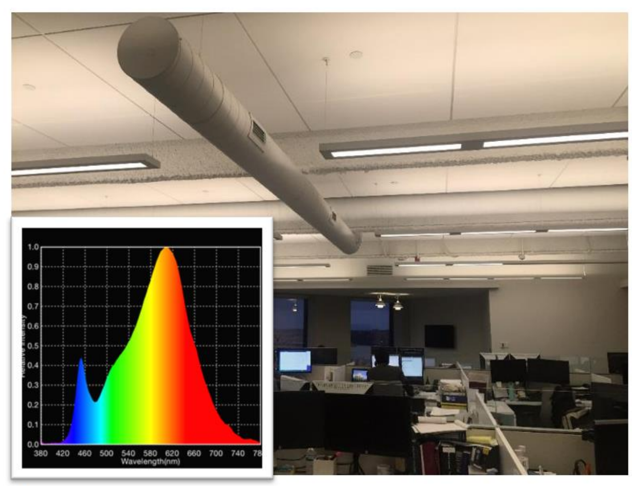
54% of workstations

75 % of workstations

Figure 8: EML Measurements at old office (left) and new office (right)



Mid-day
Color temperature
set at 5000K



Evening
Color temperature
set at 3000K

Figure 9: Operation of Circadian lighting system throughout the day

Health and Wellbeing

Strategies implemented in new office:

Access to views through windows- 78% of regularly occupied areas have access to views to Boston's waterfront and downtown area. Biophillia was integrated through the selection of materials and colors that reinforce the concept of warmth through natural finishes

Active workstation were integrated in the design- all employees have sit-stand desks. Weekly fruit deliveries are provided to encourage healthy food consumption.

In addition to this, quiet working spaces are provided, a wellness room and a large break-ouot area.

Occupant Survey results:

Only 14% of staff said they sit at their desk 8+ hours per day, compared to 40% in our old office

As a result of providing a large kitchen breakout space that has views overlooking the Boston downtown area, 94% of staff said they were satisfied with the quality of space provided to eat, as compared to 23% in our old office. 43% of staff said they feel healthier in the office compared to not in the office, compared to 2% in our old office

87% of staff agree there is a sense of community at work, compared to 65% in the old office. 72% of staff find the office environment inspiring and energizing, compared to 38% in the old office

DISCUSSION

Type of data obtained and processed

More insightful information on the effectiveness of wellness strategies was gained through the occupant surveys as this could not be measured by sensors. This also brings up the point of occupant perception of the space versus measured data. It is important to continue investigating both qualitative and quantitative data in parallel.

Sources of Data Discrepancies

It is important to note that there is a variety of factors that may have influenced the sensor results. Some of those factors include; the differences in mechanical system design and operation across the two offices, envelope properties, Glazing percentage as well as employee density. The new office also witnessed a reduction of 20% of workspace area per employee.

Online Web Tool Challenges

On the data processing level, the time based aggregations run on the tinkerforge red brick processor and are communicated to the Arup server. This means that users can only access the live data when connected to the server. Additional cloud-based technology lansdcapes should be investigated to enable external data access.

Figure 10: Online Web- Tool

In-depth System Diagnostics

Traditionally more than one sensor would be deployed in one space for more granualr results that could reveal information on mechanical system functioning and façade performance. This study was more concerned with a representation of a spatial average and hence one sensor kit was used. The study however revealed that higher CO_2 levels were present in the new office as a result of the absence of an outside air economizer, limiting the amount of fresh air intake and hence CO_2 flushing. We are currently engaging in monitoring-based commisioning which provides more detailed information on our system operations.

CONCLUSION

This paper has described the process utilized to collect environmental data on the new Arup office as well as occupant feedback and IEQ results.

The results of both the sensor analysis and occupant surveys indicate a significant improvement in the indoor environment from the old office to the new office. The quantitative data obtained from the sensor readings has shown that the biggest area of improvement is in lighting. The humidity and temperature readings show slight deviations but indicate that both systems meet the recommended temperature comfort range. While humidity increases slightly in the new office it is important to note that the occupant survey provided a higher percentage of satisfaction with thermal comofort in the new office. The CO_2 levels were slightly higher in the new office, which as noted above and can be attributed to the mechanical system design. In addition to this, other factors that can contribute to increase CO_2 levels are office employee density and façade infiltration. The higher CO_2 levels in the new office meeting room could be a result of bigger meeting rooms as well as more frequent use of these spaces as compared to our old office.

With regards to the alignment of the sensor results and occupant surveys a few points should be noted. In instances such as that of temperature and humidity it appears that the perception of comfort is higher than the actual recorded differential shows. In the case of CO_2 occupants reported higher satisfaction with the new office even though meaurements were higher. One explanation is the perception of the new office space and the fact that measurements did not exceed 800ppm.

Regarding employee productivity and cognitive performance, 68% of staff said that their productivity is positively impacted by the office's environmental conditions, compared to 8% in our old office. In addition to this, 83% of staff said they felt the current workplace supports creative thinking, activities and collaboration, compared to 37% in our old office. Additional considerations and guidance on advancing this study are highlighted in the future work section.

Future Work and Recommendations

Expanding the use of Web- dashboard will be carried out in the next stage of this study. For the purpose of this phase, the dashboard was used to provide quick access to the live data and make employees aware of their environments. In the next phase of this research we hope to start developing an internal Arup IEQ benchmark of offices as there are other offices with the same sesnor kit deployed.

Expanding Arup's IEQ Portfolio across its buildings would allow this data to be used strategically to understand and fine tune system operations. Current studies are underway to test different lighting levels and color temperatures throughout the day. This study intends to dig deeper into various effects of our adjustable circadian lighting system on employees health and productivity.

This research was facilitated by the use of in-expensive sensors that could be deployed easily in little time. Adding to the cost or complexity of set-up would inhibit the replicability of this study. We have also estimated that labour time to set up the sensors is approxiamately at 45% of total costs- which constitutes sensor costs, packaging materials as well as labor. This figure would not scale-up linearly as initial set up of time per sensor would go down as more sensors are installed.

ACKNOWLEDGMENT

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