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Monitoring Indoor Environmental Quality (IEQ) in Buildings with Distributed Sensing

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ABSTRACT HEADING

A major challenge in the built environment is the integration of energy and indoor environmental quality in the optimization of existing buildings. The UK's target of net-zero energy buildings by 2050 brings in the need to optimize existing buildings for energy efficiency and to provide better indoor environmental quality (IEQ). The complications are the monitoring of the indoor environment for better indoor air quality (IAQ) and thermal comfort without compromising the energy efficiency of the building. This paper presents the use of high-density IEQ sensor data for real-time monitoring of the space for occupant comfort and air quality. The experiment takes place in an office building in Scotland where the IEQ sensors were installed. The initial results indicate that there is an uneven distribution of temperature in the office space and poor performance of IAQ in the meeting room during occupied hours. This paper describes the initial assessment of the office space for IAQ and thermal comfort using thresholds from ASHRAE and WELL standards for analyzing the quality of the space and discusses the future development of this framework for better thermal comfort and IAQ in the indoor environment.

INTRODUCTION

Nowadays, many people spend up to 90% of their life indoors – whether at home, work, school, in transit, or for leisure (Klepeis *et al.*, 2001). And as we spend more time indoors, the quality of the indoor environment plays an important role in our health, wellbeing, and comfort e.g., (Velux, 2018). Without adequate air treatment, filtration, and dilution, Indoor Air Quality (IAQ) can become worse than outdoor air (Velux, 2018). Pathogens emitted by people, microbes, and fungi growing in the building and air conditioning systems, and pollutants produced indoors, such as from cleaning products, materials off-gassing, and combustion, all contribute to raising concerns regarding their impact on the quality of indoor air. Following this, the ongoing disruption of COVID-19 has highlighted the relation between IAQ and health (ASHRAE, 2020; CIBSE, 2020). In addition, the lack of comfort is linked to poorer performance e.g.,(Yousef Al Horr Amit Kaushik, Ahmed Mazroei, *et al.*, 2016). The growing awareness of indoor environmental quality issues is helping to drive the adoption of Indoor Environmental Quality (IEQ) criteria in green building certification schemes such as LEED, BREEAM, RESET, and WELL.

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The quality of the environment in buildings strongly depends on the design and operation of natural and mechanical ventilation strategies, indoor sources of pollutants and pathogens, the air conditioning and treatment systems used to clean or dilute pollutants and pathogens. In mechanically ventilated buildings, the operation of Heating, Ventilation, and Air-conditioning (HVAC) systems has a strong role in determining the conditioning and distribution of air in a space. While conventional HVAC systems still dominate the market in terms of volume (Research Drive, 2021), there is a growing trend for 'smart' HVAC systems driven by growth in industrial and home automation systems, sensors, and digitization. Advancements in connectivity and the Internet-of-Things (IoT) have also enabled novel approaches to operation and maintenance.

This paper examines an approach to improving IEQ through the control of conventional HVAC systems with high-density sensor data. IoT sensors were retrofitted into a conventional office at individual workstations to monitor air quality and thermal comfort. Initial results are presented from developing the distributed monitoring system for the office space. The goal of the overall study is to develop a testbed for optimal control of conventional HVAC based on numerous sensors in the same thermal and air zone.

LITERATURE REVIEW

Indoor environmental quality has a direct impact on the health of occupants, particularly "vulnerable" groups of people such as those with "… pre-existing health condition such as asthma, allergies, chronic obstructive pulmonary disease (COPD) and cardiovascular disease" (National Institute for Health and Care Excellence, 2020). Air quality standards and research have recently evolved to include not just aspects of odour control and pollutant dispersion, but also pathogen dilution and pollution ingress from the outdoors (ASHRAE, 2020; CIBSE, 2020). For example, in 2013, ASHRAE made changes to the ventilation standard 62.1 by altering the focus from CO_2 to other contaminants such as VOCs and radon in the space. It also brought some changes to the ventilation rates and improved the filter requirement from MERV 6 to 8 (ASHRAE, 2016). Given the mostly unpredictable spatial and temporal variation of indoor environmental quality, measurement and verification of outcomes are as important as design intent, sometimes more so. The recent development of low-power IoT devices has opened the possibility of scalable, distributed sensing in buildings. Broadly, IoT is the concept of using a network of numerous, distributed devices connected as nodes in a long-range, low-power mesh or hub-and-spoke radio network to send small packets of data to a cloud-based processor. IoT is widely used in several fields to remotely monitor equipment, for example. Several applications of IoT systems have been proposed for buildings, including monitoring appliances, e.g.(Min Kang, Yeon Moon and Hyuk Park, 2017), air quality monitoring (Min and Bin, 2015). Min used a ZigBee-based wireless sensor network, concluding that the detection of pollutants was sufficiently accurate, and the measurement of the indoor air system met the requirement of practical application. Grish, Rajiah and Ganesh, (2016) demonstrated the use of a simple alert system on a low-power micro-controller to monitor CO_2, temperature, and relative humidity and alert users. Airsense, an IAQ monitoring, and analytics system, was developed by Fang *et al.*, (2016) to monitor the air quality in homes using four air quality sensors to measure temperature, humidity, PM 2.5, and VOCs and upload the data to a cloud-based server. The server analysed the data from the sensors, predicted future pollution levels, and delivered suggestions to the users via a smartphone application. Lachhaib *et al.*, (2018) used IoT and big data to control the indoor CO_2 concentration using the state feedback control approach.

Particulate matter (PM) and VOCs are the common air pollutants found in indoor environments and CO_2 represents an important proxy of IAQ (Stamatelopoulou, Asimakopoulos and Maggos, 2019). Therefore, monitoring CO_2 is also an important factor for better IAQ. The VOCs in the air also constitute a major part of the assessment of IAQ. VOCs involve the risk factors for asthma, wheezing, and allergies in children (Rumchev *et al.*, 2001). VOCs comprise a lot of compounds like Formaldehyde, Benzene, chlorofluorocarbons, and more as listed in ASHRAE [Ch. 10, (Owen, 2019)]. But it is very complicated to measure every compound in the VOCs. Therefore, Total Volatile Organic Compounds (TVOC) is the best tool for screening and identifying the indoor environment for VOC concentration (Teichman and Howard-reed, 2016). Recent studies also suggest that the reason for using single term TVOC is that it is easy, simple, and faster to interpret one single parameter than interpretation of several dozens of VOCs (Berglund *et al.*, 1997).

This research article discusses the initial results obtained from the monitoring system installed in the case study building. The methodology section summarizes the experiment building's operation strategy and the data collection method. In the results section, the initial results extracted from the sensors were analysed and the insights of the thermal environment and IAQ are shown. The main contribution of this research is that existing air quality monitoring systems generally monitor PM2.5 or CO_2 along with temperature and humidity, but in this research CO_2, PM2.5, TVOC, temperature, and humidity using wireless battery-operated IoT sensors were monitored and analysed.

METHODOLOGY

Climate Study

Scotland's climate is classified as temperate and oceanic in the global climate classification (Weatherbase, 2020). The cooling season lasts from June to August, with an average daily outdoor temperature of 15ºC and the heating season is from October to April, with an average daily outdoor temperature of 0ºC (Weatherspark, 2020). Therefore, buildings are expected to have more heating than cooling needs.

Experiment Building

The office building is in Livingston, Scotland, UK. The overall building is mechanically ventilated. The office consists of 2 open space office rooms, 4 individual office rooms, and 2 meeting rooms. The open space 1 on the right side of the office is served by two Variable Refrigerant Flow (VRF) systems which provide heating and cooling to space. The top area of the windows can be manually opened to allow fresh air into space. The open space 2 on the left side of the office is served by two VRF systems and one Mechanical Ventilation Heat Recovery (MVHR) system. The individual office rooms and meeting rooms are served by either a VRF system or a split air conditioning unit. The office building is connected to the factory located in the same area. The layout of the office space and the placement of the sensors is shown in figure 1.

The office is typically occupied from Monday to Friday 09:00 to 18:00. Individual office spaces like rooms 1 and 2 normally have single occupancy. Open space 1 has six occupants and open space 2 has four occupants. During break and lunchtime, the break area in open space 2 will have around 6 occupants seated. On a normal business day, the open spaces and individual office rooms were occupied throughout the day and the meeting rooms were occupied depending on the meeting schedule. The office is operated with a heating setpoint of 20ºC during the occupied time which can be manually overridden by the individual thermostats inside each office space. The windows present in the office are manually operated. The heating system in the conference rooms will only be switched on for the length of the meeting.

IoT sensors and Data Collection

Off-the-shelf sensors were used to measure and transmit data via a gateway to a cloud database and platform maintained by arbnco. The system architecture is shown in Figure **2**. The sensors use the latest LoRaWAN technology, and they are battery operated which can last up to 10 years. This gives the flexibility to place the sensors at any location. They are placed in all workstations at a height of 1.5m from the floor level. The parameters measured by the sensors and frequency of measurement are listed in Table 1.

Key Performance Indicators

Key performance indicators (KPIs) must be defined for the project because it is the measurement of metric that reveals how the indoor environment is performing against its goals. The indicator should be easy to define, reliable, and kept as simple as possible (Bres *et al.*, 2018). Based on the measurements taken from the sensors, air temperature and humidity are indicators for thermal comfort while CO_2, PM2.5, and TVOC's were indicators for IAQ. CO_2 is a pollutant in the air because it is a common greenhouse gas that traps heat in the atmosphere and causes rising temperatures. The key sources of CO_2 inside the building are the occupants which can impede their productivity. PM2.5 refers to any particle with a diameter of less than 2.5 microns. They seem to be harmless to the naked eye, but they can travel further into the lungs. Short-term exposure can irritate the eyes and nose, whereas long-term exposure can lead to cardiovascular and respiratory problems. TVOC's potential to induce health effects vary widely, ranging from extremely toxic to those having no reported health effects. Therefore, considering the indoor environmental health and wellbeing CO_2, PM2.5, and TVOC's are measured in the proposed monitoring system.

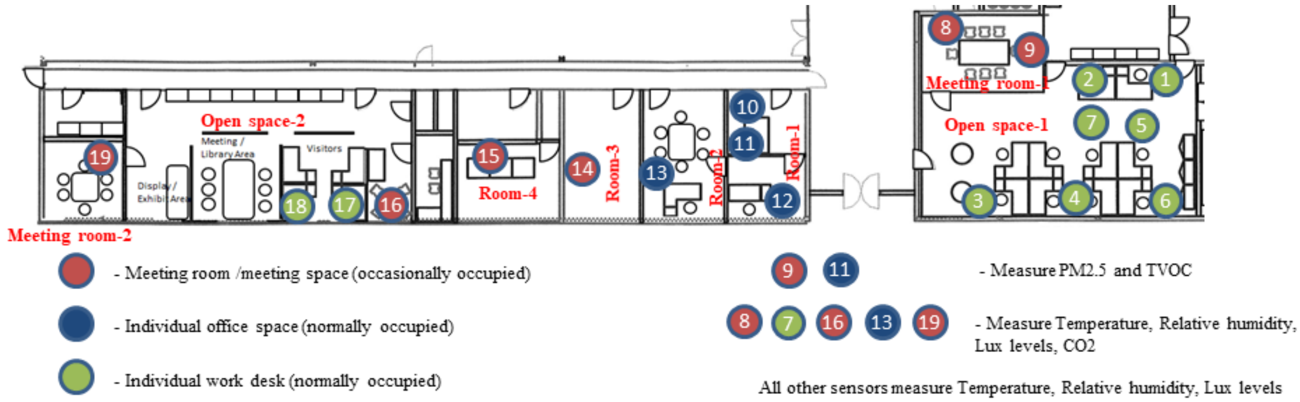


Figure 1 Sensor layout of office space

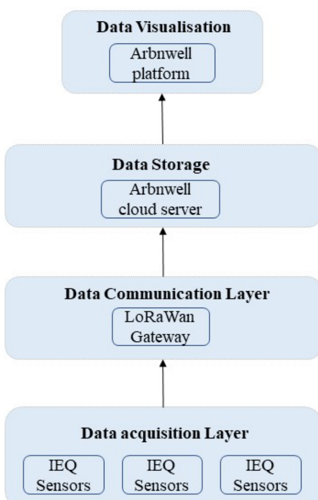


Figure 2 Overall system architecture

Figure 3 IoT sensing platform

Table 1. Parameters measured through IoT sensors

Parameters	Symbol	Units	Range	Accuracy	Resolution	Frequency
Air temperature	Ta	°C	0-50 °C	± 0.2 °C	0.1 °C	10 minutes
Relative humidity	Rh	%	0-100%	± 2%	0.1%	10 minutes
Light levels	L	lux	4-2000 lux	± 10 lux	1 lux	10 minutes
Carbon dioxide	CO_2	ppm	0-2000 ppm	± 50 ppm	1 ppm	30 minutes
Total Volatile Organic Compounds	TVOC	ppb	0-2000 ppb	± 15%	1 ppb	30 minutes
Particulate matter	PM2.5	µg/m³	0-2000 µg/m³	± 5%	1 µg/m³	30 minutes

Thresholds

The maximum CO_2 concentration permissible inside a space as per ASHRAE (Taylor *et al.*, 2016) is 1000 ppm and WELL standard (WELL, 2018) gives a lower credit if the CO_2 concentration is more than 900 ppm. Therefore, to get a better indoor performance the maximum threshold for CO_2 concentration is adapted from the WELL standard. The European directive and WHO (WHO, 2014) states that the maximum permissible limit for particulate matter with 2.5 micrometers is 25 µg/m^3. Previous research (Chiesa *et al.*, 2019) states that TVOC levels above 300 ppb are hazardous to health and it should be maintained within 100 ppb for a good IAQ. The recommended indoor temperature in an office space during winter is 21°C – 23°C and 22°C – 24°C during summer as per CIBSE (CIBSE, 2006) and the general indoor temperature in an office space for a comfortable thermal environment is 20°C – 24°C as per ASHRAE (ASHRAE, 2013). The threshold limits for the IAQ and thermal comfort set for the office space in this project are given below in Table 2.

Table 2. Threshold for IAQ and Thermal comfort parameters

CO_2 (ppm)	TVOC (ppb)	PM2.5 (µg/m^3)	IAQ Status	Air temperature (°C)	Relative humidity (%)	TC Status
<600	<100	<10	Good	21 - 23	30 - 60	Very comfortable
600 - 750	100 – 200	10 – 15	Moderate	± 1	± 10	Comfortable
751 - 1000	201 – 300	15.01 – 25	Unhealthy	± 2	± 20	Uncomfortable
>1000	>300	>25	Hazardous	± 3	± 30	Very uncomfortable

RESULTS

The data from the sensors were taken from the cloud platform and analyzed for performance. The data analysed in this research focused on the period from 01/08/2019 to 27/03/2020. This period includes the winter season and the time when the COVID-19 breakout happened in the UK and all the offices were shut and employees were asked to work from home. The temperature and relative humidity were averaged to obtain a value of each parameter for every 30min from 08:30 to 18:30. This helps in ease of data analysis. Table 3 shows the overall statistics of the indoor environment conditions during weekdays.

Thermal comfort

The maximum, minimum, and average temperature, and humidity throughout the office spaces during the weekday are shown in Table 3. The average temperature in the office spaces is similar but the maximum temperature varies in each office space. The maximum temperature in room 2 is 23°C while the maximum temperature in open space 2 is above 30°C. Similarly, there is a significant difference in humidity. Figure 4a shows the temperature distribution near each sensor. Even though sensors 1 to 7 are in the same open space 1, sensor 2 has a different median, and sensor 6 shows a lot of outliers above 27°C. This gives us insight into the spatial temperature distribution and the difference between temperatures in a single space even though both the locations are served by the same mechanical system. It can be observed that there is around 4°C difference in temperature inside the office space. Even though control set points are similar throughout the office there is a large difference in thermal comfort across the office.

The sensors in the thermal environment which showed huge variations during working hours on the 3rd and 4th weeks of March are represented in Figure 5. From the 3rd week of March, the UK government asked the people to do work from home. Therefore, in the heatmap, you can observe the difference between the temperatures in the spaces on both weeks. Week 4 seems colder than week 3. Also, there are differences in the temperature within week 3 in different locations. Sensor 15 in room 4 is quite warmer than the other spaces throughout the week.

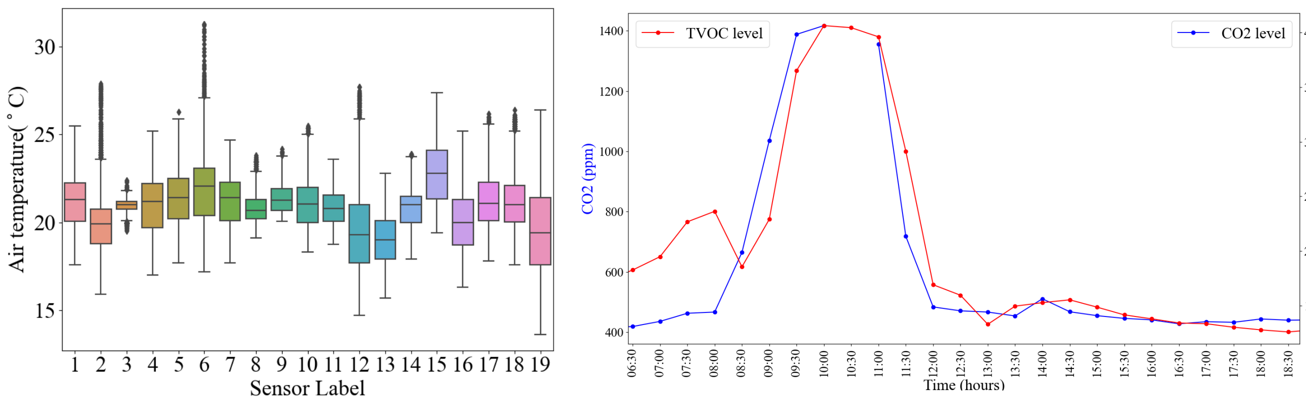
Table 3. Weekday working hours statistics of Indoor Environmental Condition

Parameters	Value	Open space 1	Open space 2	Room 1	Room 2	Meeting room 1
Air Temperature (°C)	Min	18	18.3	18.4	17.2	18.6
	Max	31.3	26.4	27.7	22.8	26.4
	Mean	21.9	22	22	20	21
Relative humidity (%)	Min	30	27.5	32	35	34.5
	Max	66	66	69	73	68
	Mean	45.6	45	47	50	48
CO_2 (ppm)	Min	324	396	-	390	400
	Max	825	792	-	1208	2004
	Mean	448	442	-	507	569
PM2.5 (µg/m^3)	Min	-	-	0	-	0
	Max	-	-	6	-	9
	Mean	-	-	1	-	1.5
TVOC (ppb)	Min	-	-	126	-	126
	Max	-	-	304	-	500
	Mean	-	-	166	-	186

Indoor Air Quality

As shown in Table 3, the maximum carbon dioxide concentration levels in meeting room 1 and individual office room 2 exceeds the threshold values when occupied. The highest concentration of 2004 ppm was measured in the meeting room and the lowest concentration of 324 ppm was measured in open space 1. The mean values range from 442 ppm to 569 ppm. This shows a wide variation in the results between the upper concentration of the meeting room and the mean value of the same room. This shows that the meeting room and individual office room 2 sensors have large outliers beyond the upper threshold limit of 900 ppm. This is because the meeting rooms were occupied only at a particular time and during that period the CO_2 concentration should have gone up.

Figure 4b shows the CO_2 and TVOC performance in technical meeting room 1 during a working day. There is a rapid increase in CO_2 levels and TVOC at the beginning of the meeting. An increase in occupants in the space led to more exhalation of carbon dioxide and a simultaneous increase in VOC gases. The meeting lasted for around 2 hours. After that when the occupants left the space, CO_2 and TVOC decreased significantly to around 400 ppm and 150 ppb respectively. Overall, the CO_2 and TVOC were very high, and CO_2 exceeded the maximum threshold of 900 ppm and TVOC exceeded 300 ppb. This was mainly due to the closed environment, and it is only connected the office room 1. The air exchange happens only through the gaps and opening of the door. From Table 3 it can be observed that PM2.5 remains well within the threshold values. Since it is a mechanically ventilated building the windows were closed most of the time. The PM2.5 value shows that the building is airtight because despite the factory being present next door, the PM2.5 values are very low during occupied and unoccupied periods.



(a) (b)

Figure 4 (a) Air Temperature distribution across the office space (b) IAQ performance in the meeting room during working hours

DISCUSSION

This paper describes the real-time IoT platform to monitor indoor environmental quality through distributed sensors. This result shows that the high-density data collection gives a clear picture of the comfort and air quality in the office near each workspace. Even though the mechanical system is distributing the heat evenly it can be noted that the air temperature is different in different areas of the office space. As discussed in the results section it can be observed that the temperature distribution is non-uniform within the workspace and in some places, the maximum temperature is only around 24ºC while in some places it is going beyond 30ºC. This creates discomfort for the occupants. Even the humidity in the space shows around 15% difference between each space.

The indoor air quality results section shows that CO_2 concentration in open space offices is well within the thresholds. This was due to the large open space and fewer occupants compared to room 2 or the meeting room. TVOC was also linked to occupants in the space. It was high in the meeting rooms due to the usage of many electronic items and the presence of occupants during periods. Due to the better functionality of the systems and airtightness, PM2.5 was always within the threshold value.

The main advantage of this monitoring system is that it gives a high picture of the spatial distribution of temperature, humidity in office space, and potential draughts. It gives us insight into the IAQ within the closed environment and their performance during occupied and unoccupied times. Due to the usage of low-power batteries, these sensors can be placed anywhere in the space, and this gives flexibility in the placement of sensors. The online IoT sensing platform gives real-time information about the space and helps to understand how the system functions and how the thermal environment responds.

The next step in the study is to integrate this into the building management system and apply different control scenarios to look at how the change in the control sequence speeds up the changes in the space. The control will focus on active systems to provide better thermal comfort and IAQ at minimized energy consumption. In addition to that, a framework to provide feedback in terms of the thermal comfort of occupants will be added so that the information on thermal comfort state and their preference can be gathered. These details can be used to implement machine-learning (ML) approaches to understand each corner of the space and classify the workspace to improve productivity and occupant comfort. Also, ML can be used to forecast indoor environmental conditions and adjust the schedule and control to prevent any critical environmental conditions.

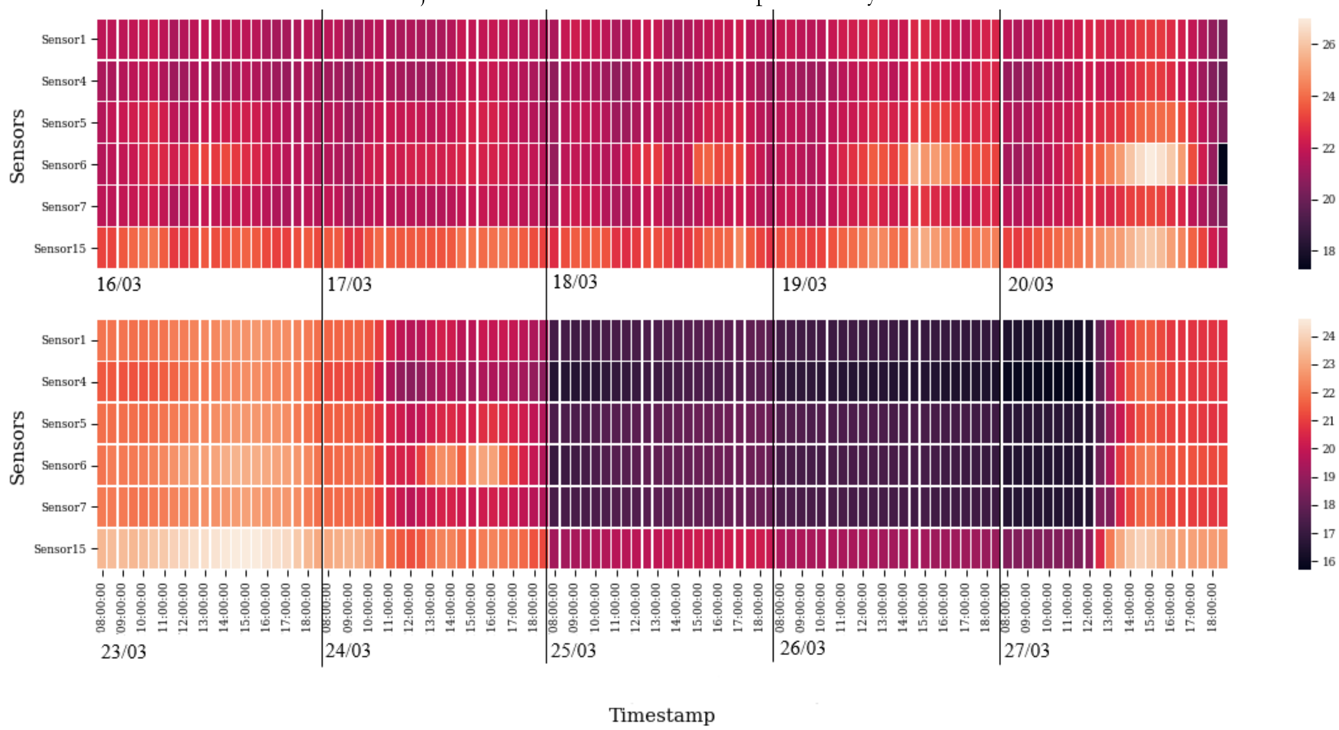


Figure 5 Heatmap of temperature during March 3rd week and 4th week

CONCLUSION

It was shown very clearly that the ubiquitous monitoring system gives an insight into the spatial distribution of thermal comfort and IAQ in the office space. Even though the average temperature where nearly the same in the office space the spatial distribution of temperature varies widely. Similarly, short-term exposure of high CO_2 and TVOC were seen. This paper investigates the use of distributed IEQ sensors placed at individual workstations and analysis of the high-density sensor data in an office. The results indicated that there is no uniform spatial temperature and humidity distribution. In addition, the IAQ in the meeting room showed poor performance during occupied hours. In summary, this research has demonstrated the use of a ubiquitous monitoring system in an office space to understand the comfort and IAQ at each work-desk of office space. The framework described in this paper was developed for ubiquitous monitoring of space and with distributed IEQ sensors and IoT sensing platforms. The future work will involve integrating the data for controlling the systems in the space.

ACKNOWLEDGMENTS

The authors would like to thank the Construction Scotland Innovation Centre (CSIC) for enabling this collaboration.

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