The Indoor Air Quality Trilemma: Improving Air Quality, Using Less Energy, and Meeting Stakeholder Requirements

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Good indoor air quality (IAQ) is critically important for many aspects of our lives, including as we've found recently in reducing the transmission of airborne diseases such as COVID-19. Delivering good IAQ can pose several challenges to organisations: it can require changes in working practices, be bounded by infrastructure capabilities such as buildings and their heating and ventilation systems, and result in substantial energy usage. In this study we have conducted a preliminary investigation measuring IAQ in a typical 'science lab' classroom, and engaging with stakeholders to jointly explore these data. Our mixed methods approach uncovers an indoor air quality 'trilemma', which relates air quality, energy usage, and stakeholder practices that can be mediated by, and understood as, a site for potentially impactful future HCI designs.

CCS Concepts: • **Applied computing → Consumer health**; • **Human-centered computing → Usability testing**.

Additional Key Words and Phrases: Indoor Air Quality, UK Schools, CO_2, $PM_{2.5}$, Classrooms, Energy Penalties, HVAC Control, Smart Sensors, Distributed Sensors

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1 INTRODUCTION

According to the World Health Organisation (WHO), poor air quality is one of the greatest environmental threats to human health [19]. For a long time, the focus has been on outdoor air quality [20], but with us spending 90% of our time indoors [13], this has widened to include indoor air quality (IAQ) too. The recent —and ongoing— COVID-19 pandemic has only served to reinforce the importance of IAQ, and saw CO_2 monitors become common in schools and offices [21] as guidance to "increase ventilation" [24] became critical to public health.

However, the need to increase ventilation rates, particularly by opening windows raised other concerns including the need to keep warm in the winter. Buildings have traditionally been designed to insulate, with many in the UK only being ventilated through opening windows. If the windows are not opened, then poor IAQ can become trapped indoors increasing the potential risk to health. At the same time, over ventilation leads to wasted energy with the potential expense of wasted heat, with heating, ventilation, and air conditioning (HVAC) systems having to work harder to maintain thermal comfort.

All of this comes at a time of climate emergency coupled with geo-political pressures on natural resources such as natural gas that has simultaneously raised energy prices and highlighted our dependence on fossil fuels. The ongoing energy crisis is again shifting priorities, with greater incentives to reduce energy bills and carbon footprint whilst retaining thermal comfort and air quality. As such, school stakeholders, such as building managers, have started to experience a real challenge balancing good IAQ with the growing cost of heating, and maintaining comfortable indoor temperatures.

We argue, the current context represents an indoor air quality trilemma: where IAQ, energy usage, and stakeholder requirements are placed in tension with one another. In this recent work, we set out to explore this IAQ trilemma via a pilot study in a UK classroom. IAQ in public spaces is often managed via energy intensive HVAC systems, both being balanced by stakeholder requirements for comfort and safety as well as reducing energy bills. School classrooms serve as an interesting site of exploration due to real world constraints and limitations, such as the need to primarily educate and safeguard pupils. Our study involves schools in the UK, and the diversity and age of the UK school building stock is also noteworthy [8].

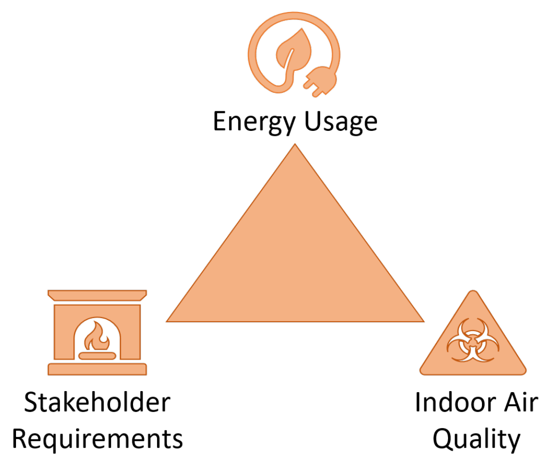

Fig. 1. The Indoor Air Quality (IAQ) Trilemma

While school classroom IAQ in the UK is governed by thermal comfort and IAQ guidelines such as Building Bulletin 101 (BB101) [1], children and teachers have arguably not until the pandemic been directly expected to have agency and control of classroom heating and ventilation. Therefore, many classrooms offer few opportunities for classroom occupants to substantially effect IAQ through natural (e.g. opening windows) or mechanical ventilation. As mentioned above this leads to energy penalties as heating systems continue to work even as ventilation is increased. Maintaining good IAQ with rising energy costs is therefore a particular challenge as energy costs are schools' second largest spend [4].

Prior research on IAQ in the classroom has found associations with children's performance [25]. Controlled studies by manipulating CO_2 level in a classroom have also found an effect on students' task error rate, suggesting the importance of adequate ventilation for learning [23]. While these indicate the importance of actionable advice, these don't focus on the link to energy usage and have a bias towards mechanical ventilation not typically found in older schools.

The study of air quality in HCI has a rich history. For example, Liu et al. [15] identified the importance of bringing narrative and lived experience to outdoor air quality data in the city with a focus on the data presentation aspect using common HCI workshop methods, a useful resource in understanding the relationships between data and occupants but includes no real-world data collection process in itself. Snow et al. [22] reported on engagement with IAQ monitors within 11 naturally ventilated offices, advocating for non-intrusive ambient displays to visualise indications of poor IAQ, both to improve understanding of IAQ, and to enable future design for human building interaction (HBI) design [2]. A framework for the visualisation and generating dialogue pertaining to IAQ is further explored by the Kim and Li [12], who created a framework detailing the links between awareness, understanding and action .

Rather than focus on direct engagement with classroom users using situated displays, our focus has been on understanding stakeholder perceptions and the lived experience of IAQ in a school classroom using a mixed methods approach. Our preliminary study contributes an IAQ trilemma expressing an interesting design space for future HCI and HBI research aiming to explore the intersection of stakeholder practice, energy usage, and air quality.

2 EXPLORATORY STUDY

The centre-point of our study is the question "*How can we understand the relationship between energy usage, stakeholder requirements, and indoor air quality?*". We set out to uncover how IAQ varied in an 'in use' classroom, and how it relates to the lived experiences of the occupants with regards to comfort, requirements, and energy usage. To do so we followed a mixed methods approach combining gathering IAQ measurements with participant interviews discussing visualisations of these data to reach a shared understanding.

Our deployment was in a laboratory classroom in a High School (pupil ages 12–16), in the North West of England. The building is 60 years old, is naturally ventilated, and is North-East facing. Fieldwork was undertaken in June 2022, during an unexpectedly warm British Summer[1]. The classroom is of mixed use, but there is one principal teacher who operates the classroom throughout the week.

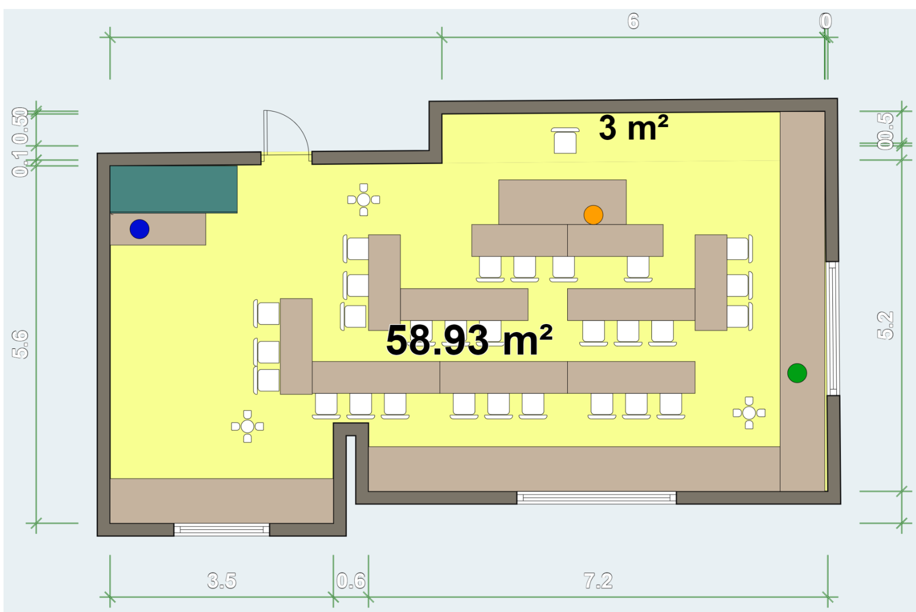

Fig. 2. Deployment classroom with notable features such as windows, desk placement, and location of desk fans illustrated. IAQ monitor locations are highlighted with coloured circles corresponding to the legend in the following graphs.

[1]https://blog.metoffice.gov.uk/2022/07/01/june-extends-run-of-warm-months

For the IAQ measurements, we deployed 3 × NAQTS V2000 IAQ monitors [16] (hereafter 'V2000') within one science laboratory classroom (Figure 2). Data was collected over a period of four weeks, and included measurements of CO_2, particulates ($PM_{2.5}$, PM_{10}), temperature, and relative humidity. Prior to deployment, all V2000 sensors were normalised through a period of calibration while co-located.

We combined the quantitative IAQ data from the V2000s with qualitative semi-structured interviews. We firstly conducted an interview at the time of installation to signpost any possible concerns or areas of particular interest, as well as to gauge the current understanding of IAQ held by the teacher (referred to further as "Teacher G") and the Head of Department. At which point the teacher revealed a concern about drowsiness of pupils in late afternoons, so we ensured that these periods were also included explicitly in the closing interview.

Following established mixed methods approach in HCI, we used the data as a resource for discussion and knowledge co-production [10] : we selected subsets of the data that revealed interesting features such as peaks in CO_2 or particulates we wished to explain, data linked to previously highlighted concerns, or where further explanation were warranted. Discussion of which would help to shed light on the stakeholder requirements and energy usage corners of our trilemma.

3 LESSONS LEARNED

In this section we outline three 'data stories' that illustrate the trilemma as it plays out in practice. We interrogate: tensions between personal agency and structural limitations in managing IAQ and thermal comfort; the lived experience of IAQ and thermal comfort in the classroom, including varying perceptions of what constitutes 'good' between different occupants; and the interplay between school specific ventilation regulations and the resulting air quality.

3.1 Building Limitations

Managing ventilation is a key factor in promoting good IAQ and energy efficiency in schools. These environmental goals have traditionally been in opposition, with good IAQ being associated with higher rates of ventilation, and energy efficiency prioritising lower ventilation rates for example by closing windows or turning fans or forced air systems off to minimise heat-loss. In the current context this dilemma has become even more pronounced with COVID-19 guidance aimed to improve IAQ through increased ventilation, versus energy crisis guidance aimed at improving energy efficiency through reducing heat loss through lower ventilation rates.

These challenges are dictated by a range of different behavioural and structural factors. For example, many schools in the UK rely on natural ventilation [11] through opening windows and doors to promote air change between indoor and outdoors, and therefore lack an even or uniform distribution of IAQ [5]. However, some schools even lack the ability to open windows, with schools having understandably prioritised safeguarding measures such as safety latches on windows. In fact, many schools across the UK follow a similar policy with 24% of schools having windows that do not open [14]. Classrooms in particular, have limitations and challenges due to factors such as increasing occupancy due to growing class sizes [17], newer and stricter rulings on IAQ following the COVID-19 pandemic, as well as safety-based limitations. A clear tension forms between the agency and personal decisions made by occupants in managing IAQ and thermal comfort whilst operating within the structural and regulatory bounds of the classroom.

Indeed, this structural limitation was outlined by Teacher G who said that "*Windows are bolted in place with Perspex... they only open a crack*."

Figure 3 shows the CO_2 levels across one day, Friday 17^{th} of June. One can see the number of peaks above what is considered an 'adequate' concentration (1000 parts per million or ppm) multiple times, corresponding with class times. There is some respite between 10:00 and 10:30 (break time) and between 13:00 and 13:50 (lunch time), periods where the room is empty and the build up of CO_2 is able to dissipate. We can use unoccupied periods of the school day to calculate the air change rate (ACH), a measurement of ventilation [6]. This classroom had just 0.35 ACH, a figure well below recommended levels [1].

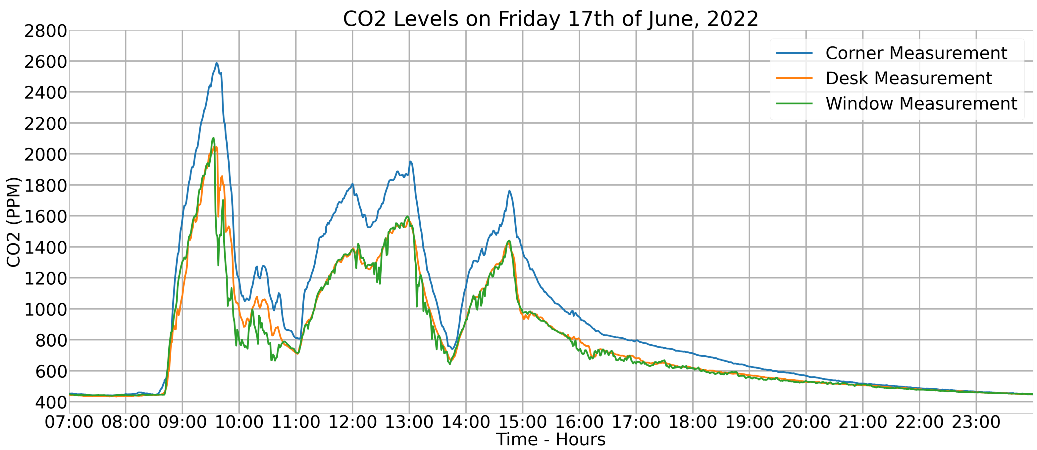

Fig. 3. CO_2 concentrations in the classroom (CO_2/ppm) on a typical day. Note the peaks and rise in CO_2 during lessons, and the decay during periods of unoccupancy and especially at the end of the day.

This was described to Teacher G as only 35.34% of the air in the room being replaced per hour. Teacher G was understandably concerned: "*If only 35% of the air is fresh then I'm breathing in the same air. . . think of the germs & dust [. . .] For a member of staff that's been teaching in there every day. . . what's the long-term impact going to be on that member of staff? Like it's quite worrying.*"

These concerns from Teacher G are understandable: the short-term effects of brain fog, headaches, nausea, and difficulty concentrating have a direct, measurable, effect on cognitive abilities [3]. The long term negative affects of CO_2 and poor air quality are also well documented. The limitations of the building ventillation in our study are evident on IAQ, even with (at the time of the study) fans running continuously. This is compounded with the limited access to outside air as windows are fitted with restrictors to limit their degree of movement to within 100mm, as advised by the UK Health and Safety Executive [9].

3.2 Spatial Variation & Differences in "Felt" Indoor Air Quality

In the first interview with Teacher G they highlighted the lack of mechanical ventilation and how they compensated for this using pedestal fans and windows to attempt to improve IAQ and comfort for their students.

Teacher G told us: "*if I had not gone in and opened the windows in the morning the children coming to my lesson will say that it's horrible in here—It's like we don't always agree.*"

Our discussion highlighted how the teacher found it challenging to achieve a temperature everyone found reasonable, and also hinted at the differing consensus and power relationships in the classroom.

This was compounded by the large size of the laboratory classroom, where Teacher G attempted to solve this in part by adding fans: "*I tend to place the fans away from my desk and so that it's impacting on the majority of the of the classroom.*"

Figure 4 corroborates the effectiveness of this strategy, highlighting the differences in temperature throughout the day at the different sensor locations. Note that the V2000 unit in the far left corner, which has less airflow (away from windows and fans), has a higher average temperature and takes longer to reach the room's background mean temperature. One can also observe that the air temperature near the teacher (orange—desk) has hotspots where it is 2°C higher than the temperature among the students (blue—window).

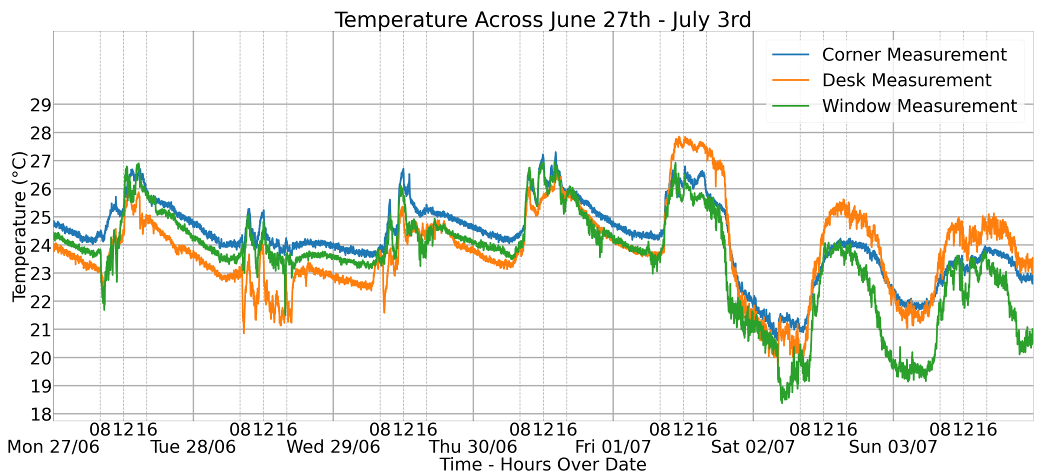

Fig. 4. Temperature levels as measured by the three V2000s across the classroom

Teacher G told us: "*I don't know... it's just moving hot air around [...] Children tend to open the windows; I have the fans on.*" Teacher G's response suggested that the fans are not having as much of an affect as they might think, lowering the temperature by a maximum of 2°C, which isn't particularly effective at creating a thermally comfortable space on the days we observed. Furthermore, the acknowledgement of both the windows and fans being on at the same time raises questions on the possibility of polluted air from outdoors being drawn indoors, directly going against what occupants' would expect: the idea of "fresh" outdoor air. Our interviews suggested the lack of empirical data on the makeup of IAQ within the classroom, coupled with the various differing needs of stakeholders and comfort preferences between the teacher and the students (in part depending on where they were sat), led to conflicting interactions on how indoor spaces are managed. Ultimately this led to inefficient compromises.

3.3 Niche Events & Changing Room Use

As part of the UK Key Stage 2 curriculum, pupils are expected to have 'hands-on time' with laboratory equipment, including experiments that involve the use of Bunsen burners [7]. BB101's most recent revision has an explicit focus on CO_2, and $PM_{2.5}$ concentrations. Perhaps unsurprisingly given that we were measuring IAQ in a laboratory, it became apparent quite quickly from the data that combustion experiments would create periods of significantly elevated concentrations of $PM_{2.5}$ (Figure 5).

With changes to the curriculum, the role of the room has changed from a demonstration led approach where the teacher performed the experiments for their students, to more individual hands-on time by each student. It could be argued that the older fume cupboards and extractors, designed for the former teaching method are no longer fit for purpose. Highlighting a tension between IAQ and ongoing changing stakeholder requirements. This begs the question, what retrofits are required to create a safe learning environment so student experience and engagement in science can be sustained alongside adequate IAQ?

Teacher G's observations on the usage and changes made to other rooms were particularly insightful: "*I've gone into other classrooms, ICT, they're cooler, they have air-conditioning*". Other parts of the school, with newer and more purpose-built facilities often have better HVAC systems to deal with the heat from apparatus such as computers and servers. Laboratories, which have featured in schools far longer than I.T. rooms tend to use older classrooms due to physical limitations of specific equipment (gas taps, access to sinks) and therefore tend to have HVAC equipment.

Figure 5 shows $PM_{2.5}$ background values of around $4\mu g/m^3$. A spike almost 25× this is observed between 12:45 and 14:00, with the peaks reaching $100\mu g/m^3$, this is several times over the recommended threshold for short term exposure to particulate matter [18]. From these data we can gather that a reaction experiment was taking place within the classroom and that the fumes were not adequately ventilated. We can observe that the window unit (green) exhibits a sharper peak than the corner unit (blue), where the ACH is lower, and the peak takes longer to return to a background concentration. The corner is a space where the air is more stagnant, suggesting a need to improve air flow, open nearby windows, or avoiding seating students within that area.

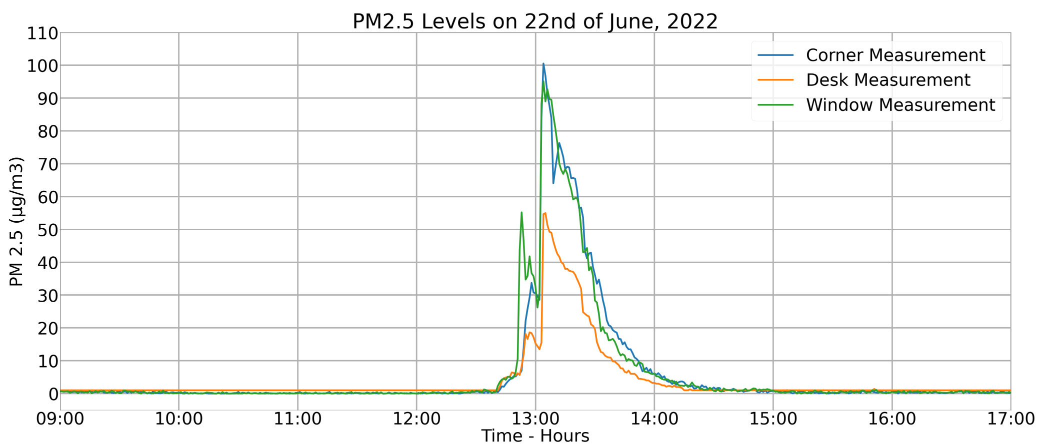

Fig. 5. A specific 'air quality event' created by the release of gasses and particulate from a combustion experiment

Teacher G explained: "*I did a practical looking at the effect of either temperature or concentration on the rate of reaction…producing sulphur […] We assume if we don't have to use fume cupboards the room ventilation will be enough…*"While the laboratory does have fumigation cupboards there simply are not enough to allow every student to use them. Furthermore with no reference within the syllabus towards regulation there is neither anything to make them aware of the health risks that significantly high $PM_{2.5}$ concentrations can have to the body, nor to advise them to increase ventilation. Even if ventilation was increased, as stated above, there are hardware limitations to the laboratory which would challenge such advice.

Our study highlights the relationship between the classroom infrastructure, such as fume cupboards and windows, its use, and the resulting IAQ. The windows can't be opened since they were upgraded to improve thermal performance. There is currently no mechanical HVAC, which were it installed, would also consume significant amount of increasingly costly energy. Once again stakeholders are unaware of the forces at play within the classroom and a point is raised that even if they are aware through changing guidelines, or situated technologies, what actual agency do they have to enact it?

4 DISCUSSION

Our mixed-methods study has helped highlight the importance of the IAQ trilemma. This exposes the relationship and tensions between energy usage, stakeholder requirements, and IAQ. We've highlighted: the structural limitations that occupants find within the classroom; the relationships between IAQ and felt thermal comfort; and the effects of the changing usage of the classroom.

The trilemma raises an important set of relationships or tensions that should be explored in future HCI or HBI. The interaction between energy usage, air quality, and the use and practices shaping this in buildings including school classrooms is under-explored. From even our simple pilot study, it seems clear that there could be a role for technology designs that unpack the relationship between air quality and stakeholder practice. Ambient and situated displays, c.f. [12, 22] might promote greater and more timely engagement with air change rates, especially during lessons that significantly reduce air quality such as those we observed with significant potential impact on occupant health. Tools could be developed that help school and building management stakeholders engage and reflect on how ongoing but less obvious changes to teaching practice, lesson planning, or retrofit to the built infrastructure could improve IAQ—with attendant benefits to learning and energy performance.

Finally, as with our future studies which will include a more diverse set of building stock, stakeholders, and occupants; the relationship between the air, infrastructure and practice that shapes energy demand—critical to addressing the climate emergency and decarbonisation agenda—suggest an important role for future sustainable HCI and HBI designs and interventions.

5 CONCLUSIONS

We have conducted a mixed methods pilot study with a classroom lab environment using indoor air quality sensors and data driven interview based methods. With 1 month of data and understandings derived from this, we highlight the complex interplay between the building infrastructure, stakeholder needs and practices, and indoor air quality. This suggests an important trilemma expressing these relationships and how they relate to energy usage.

Understanding this trilemma calls for further research on holistic (IAQ & thermal comfort) based sensor deployments in buildings, coupled in conjunction with supplementary interviews with stakeholders to gather a better understanding of the relationships with the air around us. It also represents an important site for designs to enable reshaped practices and infrastructures to improve indoor air quality and address the urgent need for effective energy and carbon reduction strategies.

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