A design thinking initiative towards studying classroom indoor climate

A K Mishra, PhD
Associate ASHRAE

E J O'Reilly, ScD

P Wargocki, PhD
Fellow ASHRAE

ABSTRACT

This pilot study explores the application of a design thinking (DT) framework to work towards creating a fit-for-purpose methodology for studying school classroom indoor climate. Conducted in three schools in the capital region of Denmark, the study engaged students and teachers as end-users to understand their needs and expectations regarding indoor climate. The DT framework, traditionally used in product design, was adapted for indoor climate research. We focused on three of the five DT phases: Empathize, Clarify, and Ideate. During interaction sessions, we discussed with students the different indoor climate parameters (temperature, humidity, carbon dioxide, and PM2.5), relevant reference levels, and potential monitoring methods. Following these sessions, classrooms were equipped with monitors to measure these parameters over a two-to-four-week period. After the monitoring phase, we returned to present summarized data to the students. Together, we reviewed the data, identified variations in readings, discussed what could be the reason behind certain patterns, and brainstormed potential mitigatory steps and long-term monitoring strategies. The outcomes of this work include the development of ideation and engagement tools, as well as feedback from the children on indoor climate monitoring. Through our work we intended to demonstrate the potential of a design thinking approach to ensure meaningful participation from end-users. This would help is design more inclusive and effective studies on classroom thermal comfort and air quality.

INTRODUCTION

Indoor air quality is a growing public health concern. In the first 18 years of a child's life, 10-15% of their time will be spent inside school classrooms (Arya *et al.*, 2024). Indoor thermal environment and air quality—collectively referred to as classroom indoor climate—affects children's comfort, health, and the teaching-learning process (Wargocki, Porras-Salazar and Contreras-Espinoza, 2019). Some studies suggest that children are likely to perceive the same environment differently from adults (Torriani *et al.*, 2023). However, current standards for indoor climate for children are often based on those derived for adult office workers (ANSI/ASHRAE, 2023), despite the significant differences in physiology, clothing choices, daily activities, and levels of control over indoor conditioning systems...

There is a need for dedicated studies on school classroom thermal comfort and air quality but conducting such studies presents unique challenges. Children are considered a vulnerable population, raising specific ethical concerns. Their school schedules are busy with a focus on learning related activities. That leaves little room for additional engagement. Designing survey questionnaires to investigate children's perceptions of indoor climate requires a more thoughtful and age-appropriate approach compared to studies involving adults (Zheng *et al.*, 2024). Traditional cross-sectional research methods, used in adult-focused surveys, may not be suitable for engaging children effectively. We need innovative, participatory approaches that prioritize the needs and experiences of children and teachers to effectively and accurately study classroom indoor climate.

Design thinking (DT), a human-centred problem-solving framework, offers a promising framework to design these innovative-participatory approaches (Brown, 2008). Originally intended for product design, DT has since been applied to

Asit K Mishra is a research fellow with the School of Public Health in University College Cork, Cork, Ireland and a visiting researcher with DTU Sustain, Technical University of Denmark. **Eilis J O'Reilly** is a Senior Lecturer in School of Public Health, University College Cork, Cork, Ireland. **Pawel Wargocki** is a Professor in DTU Sustain, Technical University of Denmark, Lyngby, Denmark.

design services, processes, and strategies. By adopting a DT framework, researchers can engage end-users—students and teachers—ensuring that their needs and expectations are adequately reflected in the study design. This approach not only foster empathy and collaboration but also enhances participants' awareness of the real-world implications (Giovanni Mainini *et al.*, 2024). For classroom indoor climate, real-world implications would include the effects of indoor climate on occupants and the impact of human behaviour on indoor climate.

A user-centred approach, encouraging sustainable behaviours among occupants is being adopted in the context of designing built environments (Giovanni Mainini *et al.*, 2024). Frameworks such as participatory action research (Montiel *et al.*, 2021), participatory design (Economidou *et al.*, 2023), and collaborative redesign (Bøjer and Woolner, 2024) have been used to involve end-users in the design and refurbishment of educational spaces. The insights from such approaches have underscored the importance of considering both engineering and human-centred perspectives in designing educational environments.

Built environment research has been gradually seeing an increase in the use of qualitative methods from other disciplines, including the social sciences (reviewed by Bavaresco *et al.*, 2020). These methods, such as Motivation-Opportunity-Ability theory, theory of planned behaviour, and perceptual control theory try to account for human behaviour in building designs and energy policies, ushering in a human centric approach. On a parallel note, human-centred design thinking (HCDT) has been used in public health education to enhance learning environments and equip students with skills to engage and help the public, rooted in empathy (Romero and Donaldson, 2024).

This pilot study explores the application of a design thinking framework to investigate classroom indoor climate in three schools in the capital region of Denmark. By focusing on the DT stages of Empathize, Clarify, and Ideate, we sought to co-create knowledge and solutions with students and teachers, providing an inclusive space to inform our research practices where children served as informants and design partners (Druin 2002). The outcomes of this work include the development of engagement tools, ideation strategies, and insights into how children perceive and interact with their classroom environment. By adopting a design thinking approach, we aimed to bridge the gap between scientific research and end-user experiences, aiming for more participatory studies in this critical area. We wanted to acknowledge the "humans in the loop" factor and engage students in studying and potentially improving classroom indoor climate. The goal was also to shift from designing products to building communities and practices.

METHODS

This work was undertaken as part of the Improving Classroom Air Quality with Student-led Solutions (i-ClASS) project. While building on previous studies that monitored classroom indoor climate, our approach differs in two key ways. First, we aimed not to only study the indoor climate of the recruited classrooms but to develop a more suitable methodology for studying classroom indoor climate, emphasizing the experiences and perceptions of children. Second, we sought to actively involve students in the process, fostering their engagement and ownership of the outcomes.

Our work had four primary objectives:

1. Improve indoor climate literacy and awareness among students regarding monitoring indoor climate parameters and understanding indoor air pollution.
2. Familiarize students with the real-world implications of poor air quality and the impact of human behavior on air quality.
3. Provide simple and effective steps to improve classroom indoor climate
4. Co-develop solutions with students tailored to the specific needs of their classrooms.

These objectives were designed to create and sustain engagement, centered around empathy, clarification, and ideation with the end-users—students and teachers.

Design thinking framework

We adopted a design thinking (DT) framework to guide the engagement. DT is a human-centered approach, particularly useful in addressing ill-defined and complex problems. It fosters collaboration and innovation. The DT process typically involves five stages: Empathize, Define/Clarify, Ideate, Prototype, and Test (Dam, 2024). However, the process is non-linear and iterative. For this pilot study, we focused on the three of the stages: Empathize, Clarify, and Ideate. We slightly modified the stages to better suit our context.

While maintaining DT's core principles of human-centeredness and iteration, we adapted the framework to our research context. The Empathize phase was a bidirectional interaction between researchers and students. The data collection was integrated in between as an effective engagement tool and to support the Clarify and Ideate phases. The Clarify phase was used to put in simple terms the challenges around classroom IAQ and how it may be studied, with inputs from students rather than define a problem statement. We focused on co-interpretation of findings as well as co-defining the challenges in the Ideate phase.

Empathize, Define, and Ideate for the classroom study context

The Empathize stage was designed as a two-way interaction to initiate engagement. We presented ourselves to the students and gathered their perspective and understanding of classroom indoor climate. We shared our personal and professional backgrounds with the students, discussing how we started in indoor climate research, what our everyday life, as researchers, looks like, and why studying indoor climate matters. In their turn, the students were encouraged to ask any questions they may have about what academic researchers do and if they had any experiences related to indoor climate that they wanted to share.

The Clarify stage involved clarifying the problem space. We discussed the parameters of indoor climate, with a focus on temperature, humidity, carbon dioxide, and PM2.5, their relevance to health and comfort, and the guidance regarding what levels are considered "okay" for occupied spaces. We also addressed the imperceptibility of indoor air pollution. For example, we discussed that compared to outdoor air pollution, indoor contaminants are a lot less visible and that presents a significant barrier to awareness and health impacts (Semenza *et al.*, 2008). To make the indoor climate parameters visible, we discussed the role of affordable indoor air quality monitoring and guidance regarding their placement. We asked the students whether there were any specific aspects in their classroom's indoor climate that bothered them and if there were any changes that they wanted to make. The students were given the opportunity to present their view on where and how they would place monitoring equipment in their classrooms (*Ideate*).

Between Clarify and Ideate, classrooms had received indoor climate monitors to deploy. After a period of 2-4 weeks of monitoring, depending on the availability of the students, we returned to the classrooms with summarized data. Together with the students, we reviewed the data, identified patterns and variations. In an Ideate stage, we focused on visualizing their classroom indoor climate and brainstorming about what the data represented and potential, easy to use, solutions. This collaborative approach allowed students to contribute their ideas and perspectives. We wanted to foster an ownership of the data and a sense of empowerment among the students regarding their classroom indoor climate. Monitoring and data analysis were important tools for continual engagement.

While we designed our framework around these three stages, DT is an iterative process. In practice, each interaction sessions involved more than one of these stages.

Recruitment and participants

We contacted *naturfagskoordinator* (science coordinators) of school groups around Lyngby to get in touch with STEM teachers in the schools. The *naturfagskoordinator* network was accessed via a publicly available Astra database (Astra, 2021). Coordinators provided our contact information to the teachers and any interested teachers could get in touch with us. The first contact was always initiated by the teachers. Through this process, we were approached by teachers from three schools around the capital region of Denmark. Two classrooms each from the first two schools and one classroom from a third school agreed to participate in this exercise. Students were aged 9–13 years. Teachers served as the primary contact points and were given flexibility in determining the level of engagement, considering the students' schedules.

Anonymity of participants (schools, teachers, and students) was maintained throughout the study and no personal data were gathered. In all sessions with students, we wanted to provide a safe space where even less confident students would feel comfortable expressing what they felt. Hence, none of the sessions were recorded and no transcripts were produced. Notes were made with pen and paper regarding inputs received from the students, in a discreet manner, and these were anonymous at source. Efforts were also made to ensure that our process was non-intrusive and respectful of students' time and contributions.

Engagement process

For all schools, we arranged a first session where we went in to introduce ourselves to the teacher and discuss further plans. During this interaction, we provided an overview of our work, the interaction session we were planning, the indoor climate monitors and monitoring phase, and how these activities could relate to STEM related activities in the student's curriculum. We emphasized that we wanted to work with teachers rather than impose our research needs on them.

The second session involved a presentation to students (Empathize and Clarify stages) where we provided background to the students. In discussions, we gauged their knowledge and gathered their opinions on indoor climate. We discussed the monitoring of indoor climate and then Ideated on where the monitors could be placed in their classrooms.

Following this session, and with feedback from the students and the teachers, we placed indoor climate monitors in the different classrooms. The duration of data collection depended on the individual class schedules (two-to-four weeks). The teachers were provided with Google Colab notebooks, coded in Python to analyse and plot the monitor data from only their classroom.

Depending on the availability of the classes, we conducted a second round of interactions with students where we discussed the indoor climate of their classrooms. These sessions were highly interactive, encouraging students to share their thoughts and ideas freely. Students commented on the levels of indoor climate parameters recorded in their classrooms, what they felt certain patterns related to, and what they felt could prevent the parameters from going outside the bounds considered comfortable/safe. This session, though intended to be built around Ideation, in practice involved each of Empathize, Clarify, and Ideate.

Table 1. Interaction session in the different schools

Session	Content	Number of schools (classrooms)	DT stages
Session 1	Introduction with teachers	3 (5)	Empathize, Clarify
Session 2	Presentation regarding indoor climate	3 (5)	Empathize, Clarify, Ideate
Session 3	Presentation of data and brain storming	1 (2)	Empathize, Clarify, Ideate
Virtual interaction	Data and tools to analyse data	3 (5)	Clarify

RESULTS AND DISCUSSION

Our interactions with students provided valuable insights into how children perceive and experience classroom indoor climate as well as research into classroom indoor climate. By adopting a design thinking framework, we were able to engage students actively in the study, fostering their curiosity and ownership of the outcomes. In one school, in addition to the classrooms, students placed one monitor in one of their laboratories as well.

Engagement and Insights from Students

Empathize phase: Students expressed keen interest in learning about the life of a scientist, including how one becomes a researcher and what activities researchers engage in outside their workday (hobbies and interests). This phase helped build rapport and trust, creating a foundation for meaningful dialogue and long-term engagement.

One important realization from this phase was the need to provide teachers and students with the flexibility to engage as much or as little as they wanted. This approach can ensure participation and accommodate varying levels of availability during classroom indoor climate research. We assured them that we would be available as per their schedule. This gave the teachers a sense of our commitment and assured the students of the importance of the topic. Further, we discussed with the teachers the ancillary learning of discussing indoor climate, such as data analysis, data presentation, the use of monitors for measuring different parameters, and broader connections to climate change and sustainable building design and to view these activities from the perspective of STEM education.

Clarify Phase: Students and teachers demonstrated some familiarity with how indoor climate is conditioned in buildings and the factors that influence it. From experience, they highlighted a lack of control over the classroom heating systems, which are centrally controlled. Many students were used to window opening for letting "fresh air" in. Many students were unfamiliar with ceiling fans, which is not unusual in this location. Students also had limited awareness of mold in indoor spaces. These discussions underscored the importance of improving indoor climate literacy among students and teachers.

Ideate Phase: The ideation process involved students in understanding indoor climate monitoring and the gathered data. It also involved brainstorming with them to co-create solutions. Some of the key realizations from this brainstorming have been listed below. Based on our interactions, students created informative videos for other children (in different classes) to inform them regarding the importance of good indoor climate and simple steps to improve classroom air quality.

1. Monitor Placement: Students identified suitable locations for monitors based on criteria such as proximity to power sources, height (aligned with "our nose"), minimal disturbance from class activities, and that no one should move it when the children were not in their class. Figure 1 shows the placement (decided in coordination with students and teachers) and the messaging (created by the teacher and students, independent of our input). The note anthropomorphizes the monitor to include it in the classroom space.
2. Carbon Dioxide (CO_2) Mitigation: Students proposed solutions such as more frequent breaks, window opening, cross-ventilation, use of fans (to increase air flow through windows), outdoor lessons, larger windows, bigger classrooms, and using CO_2 monitors to inform ventilation practices. Based on the first interaction session, some of the students had also figured out that CO_2 levels would peak when people are inside and would rise slower for a larger room. Therefore, they suggested bigger classrooms and could identify which plot in Figures 2a and 2bwere for classroom and the laboratory.
3. Particulate Matter ($PM_{2.5}$) Reduction: Students linked $PM_{2.5}$ spikes to activities such as cleaning and moving furniture. $PM_{2.5}$ levels remained low on all the monitored days, in all seven classrooms, except for one day in one classroom – Figure 2c. We were not able to relate this spike to any outdoor causes but the students from that classroom informed us that on that day, they had had some dancing in the classroom and there had been a lot of "moving around" which could explain spikes.
4. Thermal Comfort: Students noted that they knew they felt the same thermal environment differently from the teachers and other "old people". When classrooms got too warm, they suggested solutions such as adjusting clothing and opening windows.

Educational tools and resources

Through this project, we developed a resources that could aid STEM education and indoor climate literacy. We created a sample Google Colab notebook, with Python code (https://tinyurl.com/pythonCodeiClass), and indoor climate data from four days in different classrooms. The notebook uses anonymized data and is publicly available for teachers to engage students in data analysis and understanding indoor climate monitoring. We designed infographics in English and Danish to providing guidance on monitor placement (https://tinyurl.com/ICMPositioniClass) and some interactive activities with the monitors (https://tinyurl.com/engageICMiClass). Participating classrooms received coupons for books or activities as a token of our gratitude for their time and contributions. One school expressed interest in establishing an indoor climate monitor lending program, further demonstrating the impact of our initiative.

Broader implications

Classroom indoor climate is a multifaceted challenge that requires interdisciplinary collaboration. Our work underscores that it also requires a user-centered approach. Establishing genuine participation in a classroom is a challenge (Tuhkala, 2021). Built environment research is seeing a growing use of qualitative methods – focus groups, brainstorming sessions, ethnographic techniques – but there remain avenues for improvement (Bavaresco *et al.*, 2020).

By engaging students as co-researchers, we wanted to gain their perspective on both classroom indoor climate and indoor climate research. It was important that we did not come in as "experts" and valued the students' contributions. Our approach reflects the principles of citizen science which have been widely used in air pollution research to engage communities and enhance data collection processes (Varaden *et al.*, 2021). The interactions also provided the children with technical knowledge and awareness of practical issues and the built environment. We gained feedback that would improve our research and future engagements with classrooms. By involving the students, we empowered them to take an active role in addressing environmental challenges as well as ownership of the data gathered and the analysis they performed.

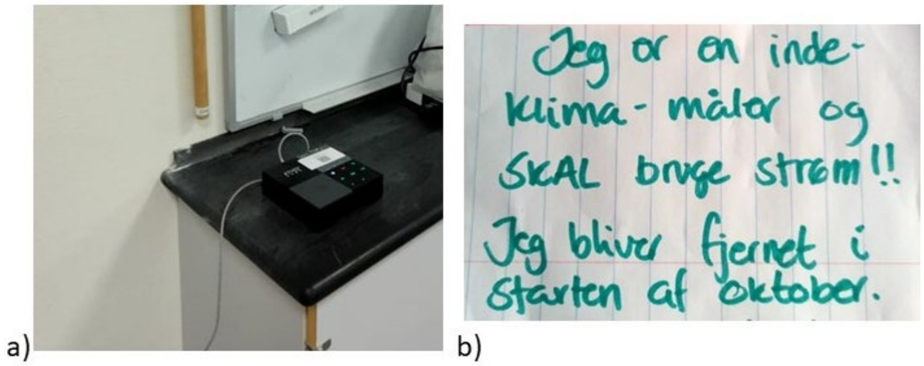

Figure 1 a) Monitor deployed in a classroom b) Note put on monitors by students-teacher in one of the schools: "I am an indoor climate meter and need power!! I will be removed at the beginning of October."

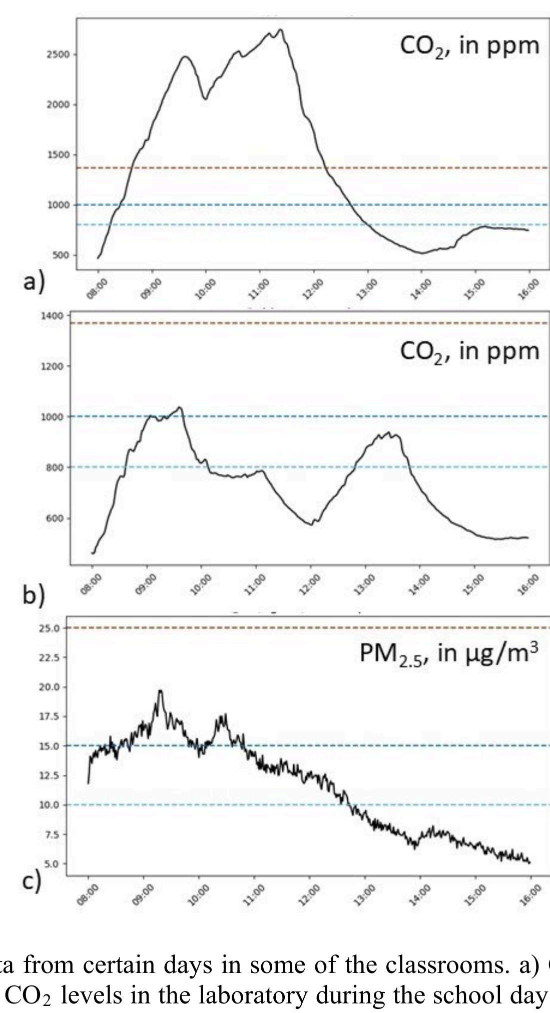

Figure 2: Plots of monitored data from certain days in some of the classrooms. a) CO_2 levels in one of the classroom over a school day b) CO_2 levels in the laboratory during the school day c) $PM_{2.5}$ in a classroom on the day the students had been dancing.

Limitations and future directions

While this pilot study demonstrated the potential of a design thinking approach for better classroom engagement during an indoor climate study, the small sample size, restricted geographical region, and short monitoring period limit the generalizability of the findings. Future studies could expand the scope to include more schools, longer monitoring periods, a broader range of interactions and expand to include the Prototype and Test stages from the DT framework to evaluate the study design and also the long-term impact on classroom indoor climate and student well-being. While our study has limitations in terms of scale and duration, it does provide a useful foundation for future research.

CONCLUSION

This pilot study demonstrated the potential of a design thinking framework to engage students and teachers in the study and improvement of classroom indoor climate. We used the Empathize, Clarify, and Ideate phases to involve end-users in the research process. This improved indoor climate literacy in community and empowered them to co-create actionable solutions. The insights gained from students highlighted the importance of considering children's unique perspectives and experiences, which often differ from those of adults. In the course of the work, we developed certain educational tools – Python notebooks and infographics – that can further support the integration of indoor climate monitoring into STEM education.

We further highlighted the value of participatory, human-centered approaches in addressing complex challenges like classroom indoor climate. By bridging the gap between scientific research and end-user experiences, we can create more inclusive, effective, and sustainable solutions for studying and creating healthier learning environments. As students are going to be the thought leaders and sustainability leaders of the future, it is logical for them to be a part of the discussions around indoor climate, comfort, and wellbeing.

ACKNOWLEDGMENTS

Asit Kumar Mishra is a DOROTHY co-fund Fellow and Marie Skłodowska-Curie Fellow and receives funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101034345. The activities in this work were funded by a Fonden af 20 December grant. We are grateful to Prof. Jørn Toftum for his help with contacting and recruiting schools.

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