A BREATH OF FRESH AIR: TOWARDS OPTIMAL INDOOR AIR QUALITY

INVESTIGATING INTERVENTION STRATEGIES FOR ENHANCING OCCUPANTS AWARENESS, COMFORT AND HEALTH

SUBMITTED IN PARTIAL FULFILLMENT FOR THE DEGREE OF MASTER OF SCIENCE

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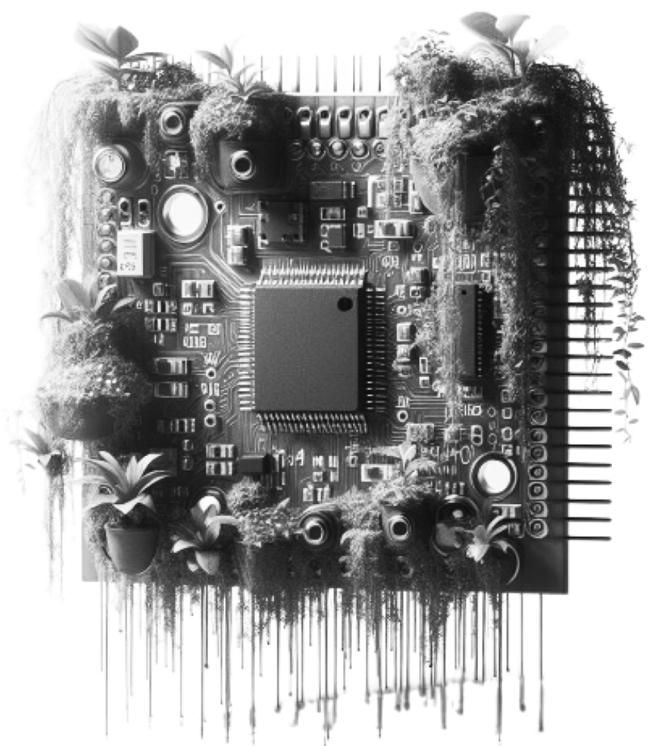

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ABSTRACT

Suboptimal Indoor Air Quality (IAQ) has been identified to pose health risks and affect the cognitive performance of occupants within indoor environments. The study investigates occupants' awareness and perceptions of IAQ, facilitating occupants' adoption of preventive measures. Employing a user-centered mixed-methods approach, the research employs Post-Occupancy Evaluation (POE) methods to elicit occupants' understanding of indoor air quality and utilizes sensory monitors to collect and measure common pollutants in specific indoor environments. These insights guide the development of 'Phair', an interactive data physicalization that visualizes real-time air quality data which was subsequently evaluated and usability-tested with occupants. The results of the user study reveal a lack of awareness among users regarding indoor air quality, while evaluations of the prototype demonstrate that physical hardware displaying real-time data can effectively increase occupants' awareness.

KEYWORDS

Human-Building interaction, Indoor air quality, Living Lab, Data physicalization, Smart buildings, User-centered design.

1 INTRODUCTION

Globally, it is estimated that people spend approximately 90% of their time indoors [30, 45] and breathe 11.000 liters of air per day [14]. Suboptimal indoor air quality (IAQ) conditions affect building occupants' experiences of comfort and insufficient ventilation in indoor environments is proven to play significant roles in occupants' well-being, health, and cognitive functions [28, 54].

The perceived comfort of occupants is influenced by the overall Indoor Environmental Quality (IEQ) consisting of several key metrics (e.g. mechanical ventilation, temperature regulation, natural lighting) to create a combined IEQ index for a specific indoor space [31]. Among these metrics, indoor air quality stands out as a crucial factor deserving special attention due to its invisibility to occupants [47], polluted air goes undetected by smell or sight, underscoring the importance of monitoring and maintaining optimal indoor air quality.

Furthermore, mechanical ventilation systems in buildings operate discreetly and are frequently insufficient for ventilation in densely populated small rooms like meeting rooms, laboratory offices, or hot-desking work areas [46], which contributes to occupants' perceived lack of control. Since these systems are typically automated [38] and cannot be directly regulated or controlled by occupants themselves [27].

This creates an interplay between occupants' effects on comfort, built environments, and computing technologies (see Figure 6) researched in an overarching interdisciplinary field of study, known as Human-Building Interaction (HBI) [1]. This research specifically focuses on understanding occupants' needs through in-the-wild [42] studies gaining insight into occupants' awareness, collecting indoor air quality data in designated spaces, prototyping data physicalization devices to visualize indoor air quality, and using these designs as data probing tool [58] evaluating their effectiveness with the overarching objective of obtaining insights into occupants' comfort levels and facilitating their adoption of preventive measures against poor indoor air quality [57].

While research on defining comfort within indoor buildings [2], gathering and analyzing sensory air quality data [14], and the effects of poor air quality are prevalent [30], there remains a research gap in understanding occupants' behavior and their subjective needs, along with limited research on how design solutions that visualize environmental data and computing installations can empower occupants, particularly within the field of physically visualizing data to convey IAQ to building occupants in real-time.

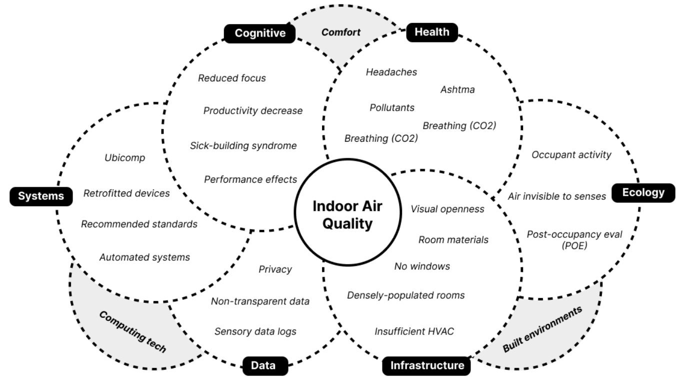


Figure 1: Complexity diagram providing an overview of the effects of IAQ and needs of occupants [2, 14, 28, 30, 45, 54]

1.1 Research questions

In order to research intervention strategies for improving indoor air quality, the following main research question is formulated:

RQ: How can real-time sensory measurements and future predictions of air quality be physically visualized in specific indoor spaces integrating both environmental information and elements that increase awareness among occupants facilitating their adoption of preventive measures against poor air quality?

To effectively answer this main research question, this research is guided by the following supporting sub-questions ("sq" for "subquestion") that also serve as objectives to delineate the necessary knowledge:

- SQ1: *How do occupants perceive and understand subjective properties of indoor air quality and their willingness to adopt preventive measures?*
- SQ2: *How can environmental information related to air quality, such as pollutant concentrations and ventilation rates, be incorporated into a physical data-driven representation?*
- SQ3: *How does the post-installation evaluation of a prototype design solution impact occupants' perceptions and behaviors regarding indoor air quality?*

2 RELATED WORK

Given the focus of this research is studying Human-Computer Interaction (HCI) within Built Environments (BE), this research draws from various related work including the subfield of Human-Building Interaction (HBI) (see Section 2.1) and subsequently narrows its focus to Comfort withing Buildings with Post-occupancy evaluation (POE) (see Section 2.2) and Indoor Air Quality (IAQ) (see Section 2.3) for the scope of this research. Furthermore, it examines notable findings from previous approaches to mapping and encoding sensory data in a new area of research called Data Physicalization (DataPhys) (see Section 2.4).

2.1 Human-Building Interaction

Buildings increasingly incorporate new forms of digital interaction [34, 39], which means new inherent connections between 'people', 'built environments', and 'computing' research in an area called Human-Building Interaction (HBI) [1, 52]. This research area is dedicated to exploring the design of built environments that may incorporate computing to varying degrees [49]. A logical extension where indoor spaces are increasingly retrofitted with sensing devices [39]. Understanding how people use different spaces in a building through computing can inform design interventions aimed at improving the utility of the space and the well-being of occupants. [53].

Current research into architecture and built environments indicates that a significant portion of the data collected by these computing devices is not necessarily transparent or comprehensible to occupants [44], and indoor spaces are designed without much thought of placing computing devices integrated within the environment [25, 29] leaving users with a perceived lack of control over their indoor comfort.

2.2 Comfort within buildings

Indoor occupant comfort is achieved in interaction with the environment and is represented in four respective dimensions; thermal, respiratory, visual, and acoustic [2]. Indoor Environmental Quality (IEQ) [31] indexes serve as metrics for assessing the aforementioned properties of comfort within indoor environments with Post-Occupancy Evaluation (POE) [18] and Perceived Environmental Qualities (PEQ) [47] methods being employed to gauge occupants' perceived comfort [10].

Studies on indoor environments focus on 'static' IEQ conditions using sensors to sense environmental conditions based on the buildings' physical characteristics to meet various recommended standards such as ASHRAE 62.1 [1], ISO 16814 [2]. Discrepancies between measured IEQ conditions and occupants' perceptions have also been reported in studies. For instance, research indicates that occupants generally have a low awareness of Indoor Environmental Quality (IEQ). While occupants perceive the environment as 'satisfactory', actual sensory measurements within the environment reveal quality levels below recommended standards. [47]. Recent studies have shifted their focus towards the active role occupants play within the built environment, viewing their behavior within a building as akin to a 'living ecology' [32] rather than perceiving comfort solely as 'static' properties of the building itself.

2.3 Indoor Air Quality

A suboptimal indoor environment has reportedly been associated with health-related problems such as headaches, throat irritation, and asthma [30] as well as a decrease in cognitive functions such as tiredness, effects on performance and productivity and a lack of focus [54] [17]. A phenomenon referred to as the Sick Building Syndrome (SBS) [20, 37]. Many of these symptoms are primarily associated with respiratory comfort and are closely tied to Indoor Air Quality (IAQ) concerns [28]. Effective ventilation strategies have been shown to significantly alleviate SBS symptoms [20].

The advancements of real-time IAQ monitoring systems leveraging Internet of Things (IoT) sensor technology have facilitated progress in both the measurement of IAQ and the implementation of interventions aimed at enhancing it [36]. Indications of poor air quality are gathered by measuring common pollutants with a focus on molds and allergens (humidity), volatile organic compounds (VOC), and carbon dioxide (CO2) [30] where occupant behavior and the number of occupants within indoor space have a specific negative effect on CO2 levels [19]. These indoor climate factors are related to the building occupants' behaviors and need special attention to be considered in assessing the IEQ conditions and determining if adequate ventilation is present [17]. It is crucial to recognize that when occupants experience symptoms, it signifies that a suboptimal air quality situation has already occurred.

The existing literature on IAQ offers quantifiable and validated methods for measuring IAQ through sensory data. It underscores the complexities associated with IAQ and emphasizes the significance of developing solutions to ensure occupants receive adequate ventilation.

2.4 Data Physicalization

The research domain known as data physicalization [3, 24] has emerged as a notable area of study, emphasizing the creation of physical data visualizations making the invisible tangible and interactible by encoding data in physical artifacts [40]. This shift from focusing on individual artifacts to a broader environmental context facilitates the physical embodiment of computing [16]. Data physicalization has the potential to positively influence the perception and exploration of data [24, 51, 55], presenting distinct advantages over traditional 'screen-focused' data representations, such as 2D canvas displays (e.g. digital dashboards) [21, 23], particularly in the context of Indoor Air Quality (IAQ) where a 'physical data visualization' serves as a fitting metaphor for rendering 'invisible' indoor air.

These tangible artifacts usually come in the form of ubiquitous computing (ubicomp) [9] device that seamlessly blends into the environment, essentially making the computing devices 'disappear' [56]. These devices are frequently employed as persuasive technology, strategically designed to gently nudge individuals towards behavior change leveraging the emerging notion of pervasive sensing to subtly enhance users' awareness regarding the impacts of their decisions [7, 41]. This method of persuasive design serves as a powerful tool in calmly extending users' awareness, helping users

[1] https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2
[2] https://www.iso.org/standard/42720.html

understand gathered data, and the consequences of their actions, and gaining insight into their behavior [8]. A systematic analysis of over 60 representative data physicalization papers [43] show that only numerous (f=3) approaches to studying computing devices within indoor spaces and interactivity with occupants have been explored in prior research especially with a focus on indoor air quality to nudge occupants to a desired behavior. This framework of data physicalization and persuasive technology establishes the theoretical foundation for the creation (prototyping) and the evaluation (usability testing) of the design solution within this research.

3 METHODOLOGY

To answer the research question this study uses a human-centered approach (often referred to as Design Thinking) commonly found in Human-Computer Interaction studies consisting of four phases; 1) user studies to *understand* the user, 2) *data collection* methods and analysis of the situation as field trials, 3) *ideation* and experimental design of a prototype and 4) *evaluation* and usability testing of the prototype [26, 58]. This mixed-methods approach (both qualitative and quantitative) helps understand occupants' needs and informs the design and technical set-up of the prototype evaluating the effectiveness by focusing on the user's needs from the start of the study [35, 42]. For the first phase, an online questionnaire was conducted to *understand* occupants' awareness of indoor air quality (see Section 3.2), for the second phase a lab setting was created with IAQ monitors to do *data collection* and gain insight into environmental data (see Section 3.3) which in turn informed phase three the *ideation* and creation of the prototype (see Section 3.4, Section **??**). In the last phase participants *evaluated* the prototype and performed usability tests (see Section 3.5). The concepts of indoor air quality monitoring and data physicalization were investigated through literature review and desk research before setting up the survey, creating the prototype, and conducting the evaluation interviews.

3.1 Case study building

This study will be conducted in association with the Digital Interactions Lab [3] and will utilize the recently opened Lab42 [4] building at the UvA Amsterdam Science Park [5] as its primary case study location (see Appendix H). Lab42 is an energy-neutral, flexible, and adaptable faculty building that facilitates collaborations among students, researchers, and businesses [6].

Figure 2: Impression photographs of the case study building

[3]https://uva-dilab.com/
[4]https://lab42.uva.nl/
[5]https://www.amsterdamsciencepark.nl/

3.1.1 Space usage. The buildings's layout is strategically organized into different zones, each serving various functions, ranging from quiet individual work to spaces that allow for collaborative work. Lecture halls, learning rooms, and open learning spaces make up the two lower floors, with the upper four being primarily assigned to the university academic staff, meeting rooms, and external offices. The overarching interior theme in the design revolves around 'tech' and 'nature' aiming to cultivate a fresh, light, and warm comfortable ambiance. Lab42 is an example of a smart building or living lab where sensing devices are retrofitted throughout the building to automatically adjust lighting, temperature, and the focus of this research regulating air [5]. This already provides a base of environmental data that can be used and extended for further analysis. Since most of the space within the building is designated as informal learning space and another large part of the building is designed as meeting rooms (see Appendix G), working areas these functions of focussed work and collaborative meetings can be heavily influenced by reduced cognitive performance as a result of poor indoor air quality.

3.2 Questionnaire survey

To understand and collect occupants' subjective awareness and satisfaction of IAQ a structured survey was created to gather quantitative data within the building as a form of Post Occupancy Evaluation (POE) (see Appendix M).

3.2.1 Questions. The questions were based on two POE studies with a focus on indoor air quality [46, 47] and used standardized questions (e.g. Q-bank) and scales (e.g. Likert-scale). The survey consisted of a total of 9 questions (5 multiple choice, 3 Likert scales, 1 not mandatory open question) consisting of questions about:

(1) *Activity and occupancy:* the rough location the occupant is within the building, how often the occupants use the building for various activities, and how they would describe the occupancy in their current space.
(2) *Awareness and satisfaction:* how aware the occupant is of the current air quality in the space, how the occupant perceives the air quality in the current space, and how satisfied the occupant is with the air quality in the current space.
(3) *Health and cognitive symptoms :* if the occupant experiences any health or cognitive symptoms based on the air quality in the current space.

3.2.2 Participants. The survey was distributed via handouts with QR Codes using eligibility criteria based on demographic characteristics to occupants present at the informal learning spaces of the atrium, first floor, and second floor. There were no additional inclusion criteria besides the convenience sampling size of respondents being present in the case study building (sampling in context). Additionally, handouts were attached to the tables using stickers. All instances of participation were voluntary and conducted without remuneration. Distribution of the survey was open for submission from the 1st of March to the 31st of April 2024 which recorded X (n=X) responses in total of which after cleanup a total of X (n=X) responses were included in the final dataset. No personally identifiable information such as age and gender was collected during the survey and ethical considerations (e.g. consent forms) were taken into consideration. To improve the quality of the questionnaire on the initial version feedback was requested, after which the survey protocol was piloted, before distributing to participants (see Appendix C).

3.2.3 Data cleaning, preprocessing and analysis. After the distribution of the survey completed analysis of the collected data was performed in the form of data cleanup and exploratory data visualization. In Python (Jupyter Notebook format) [6] Libraries such as Numpy [7] were used to clean the data (e.g. remove non-consenting users) and visualization libraries such as Seaborn [8] were used to create graphs and plots (e.g. boxplot the likert-scales) to get an overview of the collected data and gain insight into understanding the occupants.

3.3 Air Quality Monitoring

To gather data about the current situation of air quality within the building and understand the current situation within the building in terms of air quality data we retrofitted IAQ monitors to two specific meeting rooms within the building (see Appendix F). This data collected was further used to inform and acted as a basis for the data input of the data physicalisation (see Section **??**).

3.3.1 Technical set-up. We deployed the monitors in meeting rooms occupants regularly use which allowed us to understand occupants' behavior and perception in real-world corporate settings as opposed to a controlled lab setting. We refer to them as the small room (room A) and the large room (room B). The small room is XX m2 and is commonly used for small-size meetings (seven seats), while the large room is XX m2 (fourteen seats), which is preferable for hosting larger-size meetings and seminars. Two commercially available indoor climate data loggers were installed using 3D printed mounting plates, an AirCheq Touch Aero [9] in the smaller room and an Atal ATU-CT ClimaTrend [10] in the larger room. Both monitors use industry-standard (e.g. Senseirion and SenseAir) sensors to measure common pollutants and were mounted (e.g. between 80cm and 120cm from the ground) and calibrated (e.g. intervals, polling rates) as described by both manufacturer's installation manuals. The monitoring devices were installed from the 1st of March to the 31st of April 2024

Table 1: Subset sample data of the IAQ monitors

Time	Humidity (%)	VOCs (ppm)	CO2 (ppm)
08:00	40	0.05	500
09:00	42	0.06	520
10:00	45	0.07	550

3.3.2 Data logs. The data gathered by the sensors provides insights into various standardized measurements related to common pollutants that affect IAQ such as molds and allergens (humidity), volatile organic compounds (VOC), and carbon dioxide (CO2) (see Table 1, Appendix L). We cross-referenced the data logs with weekly schedules based on the internal booking systems of the rooms based on the timestamped data to align the values of the sensors from the data logs when meetings were scheduled. Data analysis is performed similarly as described in (see Section 3.2.3). were data was cleaned to remove data from mainly non-opening hours and plotted and visualized to explore patterns in the data and cross-reference them with meeting times.

3.4 Ideation and requirements

As a starting point for creating a physical representation of the air quality data we base our formative research on the growing interest in establishing theoretical and design foundations for *data physicalisation* [8, 21, 43] on how to encode the properties and use a common design language [40, 48] established by systematic reviews of data physicalization projects. The overall goal of the prototype is described in the following definition:

> *a data-driven physical artifact whose geometry and material properties encode data that aims to augment a nearby audience's understanding of data insights.*

Before prototyping the design solution we first describe the overall requirements and scope of the physicalization and case studies used for ideation. The final prototype is described based on the encoded variables and design dimensions found in the literature (see Section **??**).

3.4.1 Concept requirements. Based on this scope and the survey we describe the concept requirements ("r" for "requirements") of the design solution in further detail with six overarching requirements ranked based on the Moscow method:

- R1: **Visual Feedback:** The prototype must provide visual feedback through movement encoding environmental properties that represent air quality metrics, ensuring that users can easily interpret the information conveyed (must have).
- R2: **Size and location:** The prototype must be designed to be installed within small to medium-sized rooms, with consideration for its dimensions and weight to ensure compatibility (must have).
- R3: **Real-Time Data Integration:** The prototype should integrate real-time data from air quality monitors to dynamically adjust its behavior (should have).
- R4: **Interactive sensing:** The prototype should be interactive in which occupants can interact with the prototype by walking near it providing a tactile experience (should have).
- R5: **Material durability:** The prototype could use natural materials and be durable and resistant to environmental factors such as humidity and temperature fluctuations (could have).
- R6: **Aesthetic Integration:** The prototype could seamlessly integrate with its surrounding environment, complementing interior design aesthetics, architectural features, and layouts of the room to enhance the overall ambiance (could have).

3.4.2 Concept models. For the concept models, two existing datasets of academic and non-academic case studies were used as comparative studies, desk research, and as a starting point for ideation. First

[6] https://jupyter.org/
[7] https://pandas.pydata.org/
[8] https://seaborn.pydata.org/
[9] https://airteq.eu/producten/touch-aero/
[10] https://www.atal.nl/atu-ct-climatrend-binnenklimaat-datalogger

(a) Placeholder caption **(b) Placeholder caption** **(c) Placeholder caption**

Figure 3: Impressions of the ideations and prototyping phase

was the DataPhys gallery [11], a collection of 372 entries classified as data physicalizations. The second was a combination of three state-of-the-art papers with systematic reviews of physicalization with combined examples of around 132 entries classified as data physicalization of which both academic and non-academic samples [4, 40, 43]. Out of these, seven (f=7) samples of academic were selected for further review based on the similarity with the before described requirements of which three (f=3) samples with a focus on the environmental property of air, but not necessarily air quality within indoor environments (see Appendix T). Additionally, fifteen (f=15) samples of non-academic case studies were reviewed after desk research which included work and prototypes from design studios and independent creators that informed the ideation phase (see Appendix U).

3.4.3 Concept diagrams. Based on the user requirements and ideation and concepting from the Communication and Multimedia Design (CMD) Methods Pack [12] and Design Method Toolkit [13] by the Digital Society School (DSS) three low fidelity (lo-fi) concepts were further elaborated (see Figure 4a) in order to choose one to develop in high fidelity (hi-fi) for the user studies and evaluation.

(1) **Concept-1: Desk Planter (Aspen)** A desk planter or tree in the corner of the room with soil in it.Follows the organic growth of a 'seed' of a flower or tree from seed to sprouts to full flower. The better the air quality the more or faster the plant grows. The movement of the leaves can indicate the wind.
(2) **Concept-2: Hanging Sculpture (Bluebird)** A hanging planter-type set-up with strings that 'grow' from the ceiling. Fresh air moves the strings. People can walk by, and feel the material (e.g. humidity). Allows most interactivity. Taking inspiration from kinetic sculptures and hanging/floating sculptures.
(3) **Concept-3: Wall Kinetic (Crocus)** A moss-like structure on the wall with flower bulbs embedded. The flowers 'open up' based on better fresh air. Taking inspiration from kinetic sculptures.

Concept selection was based on weighted physicalization criteria from the literature, a Harris profile for the lo-fi concepts, and four expert reviews (n=2 internal experts involved in the project, n=2 external experts not involved in the project) feedback (see Appendix **??**, Appendix **??**). Also technical limitations of the provided hardware (e.g. real-time data output of monitors, cost of hardware, availability of electronic components,) and limitations in the technical set-up of the building (e.g. space in the meeting rooms, not allowed to alter furniture) were considered as heuristic evaluation. Based on the aggregation of these criteria the *Bluebird* concept was chosen to be further developed into a high-fidelity prototype (see Figure **??**, Appendix I).

3.5 Evaluation

The prototype was evaluated as summative research using common performance-related criteria that are widely used in HCI/Information Visualisation [40] and Grounded Theory studies [13]. We employed a field-based evaluation approach with accompanying methods based on the Human-centered Design Kit by Ideo [14] and Delft Design Guide from the Delft University of Technology (TU) [15]. For evaluation criteria, we used the intentions and evaluating interview methodology described in the data physicalization design vocabulary [23, 40] as a baseline for evaluating the efficiency, and memorability using in-person evaluation sessions. To measure the overall effectiveness and usability of the physicalization we based and adopted questionnaires of the Technology Acceptance Model (TAM) and System usability scale (SUS) to gather insight into perceived usefulness, attitude towards using, and system usability scale [11, 15].

3.5.1 Hypothesis elicitation. Based on the research question and creation of the prototype three hypotheses ("h" for "hypothesis") were formulated to evaluate as an observational study:

H1: **Understanding:** users will exhibit a clear comprehension of the physicalization's representation of IAQ data, as well as an understanding of its intended function and impact
H2: **Self-reflection:** users exposure to real-time IAQ data visualizations through the prototype will prompt users to reflect and will lead to increased awareness.

[11] http://dataphys.org/list/gallery/
[12] https://cmdmethods.nl/
[13] https://toolkits.dss.cloud/design/
[14] https://www.designkit.org/methods.html
[15] https://www.bispublishers.com/delft-design-guide-revised.html

H3: **Effectiveness:** users acceptance and satisfaction with the IAQ physicalization will be positively correlated with perceived usefulness, attitude towards use, and system usability.

3.5.2 Participant sampling. The sample size of evaluation interviews was x (*n*=X) and accepted because the study findings reached theoretical saturation, new interviews did not yield new insights after the first x interviews and led to repetitive data [50]. Participants were gathered through purposive sampling and were not involved in the development of the prototype. Respondents had to meet the inclusion criteria ("c" for "criteria") that needed to be checked before the interviews:

C1: The participant needed to use a meeting room with the building a minimum of once a week
C2: The participant needed to work within the case study week a minimum of 3 days per week

This resulted in a sample of x male, x female, consisting of various roles; from researchers from different labs, PhD candidates working at the labs to private company employees encompassing a range of ages (*min*=x, *max*=x, *mdn*=x) and education levels of which x (*f*=x) participants were acquired through snowball sampling. Participants used the meetings rooms on average x (*min*=x, *max*=x, *mdn*=X) a week and worked within the lab42 building x (*min*=x, *max*=x, *mdn*=X) a week. The evaluation session where held between May 1st to 31st of May 2024

3.5.3 Evaluation interviews. Within the meeting-room lab set-up in the presence of the developed prototyped pre-arranged, semi-structured individual qualitative interviews were conducted with open-ended and nonleading questions with additional in-depth questions (follow-up probing strategy) on topics emerging from the dialogue (see Appendix P). To improve the quality of the interviews (and evaluation session in general) on the initial version feedback was requested, after which the interview protocol was piloted, before continuing with participants (see Appendix C). The goal was to gather first impressions and gain insight into how occupants understand the communicated data factors of the prototype.

3.5.4 Participant observation (usability testing). After the explorative questions participants were encouraged to in more detail view the prototype and interact with it as a field trial stating anything they noticed (encouraging probing strategy). Participants' behavior was observed within prolonged engagement in the meeting rooms and participants were encouraged to think aloud when viewing and interacting with the prototype (see Appendix Q). Informal leading questions were asked about improvements, design optimization, and visual changes. In this manner, insights into particular interaction elements were acquired without the explicit involvement of HCI specialists. The goal was to test the usability of the prototype, study occupants and their behavior in a natural setting, and gather insight into the self-reflective properties of the prototype.

3.5.5 Prototype effectiveness. After the interviews and observations, the participants were asked to fill in a digital online with structured pre-defined questions form rating several properties of the prototype for their effectiveness (see Appendix R). The goal was to gather quantitative measurements about the usability and effectiveness of the prototype.

3.5.6 Transcription and coding. All interviews were anonymized and conducted in-person on-site and audio recorded with permission of the participants. The recordings were then verbatim transcribed using the built-in Microsoft 365 transcription tool [16] to avoid bias while note-taking. The transcribed interviews as textual data were processed via Atlas.ti [17] for qualitative coding.

4 RESULTS

The goal of the chosen methodologies (see Section 2) allows for answering of the (sub)research questions. First, the results of the questionnaire survey are described (see Section 4.1) and key insights into the air quality monitor data collection are presented (see Section 4.2) to answer SQ1. Then the developed prototype will be presented in section (see Section 4.3) which addresses SQ2 and the results from the evaluation sessions will be summarized in (see Section 4.4) to address SQ3.

4.1 Survey analysis

The following section presents the outcomes of the survey conducted to assess various aspects related to occupants' activity, IAQ awareness, satisfaction, perception, and health impacts among Lab42 building occupants. The responses show that most occupants are located in the atrium of the building, not particularly aware of the IAQ, and perceive the IAQ as acceptable based on the large open area and planters, meeting satisfactory IAQ levels.

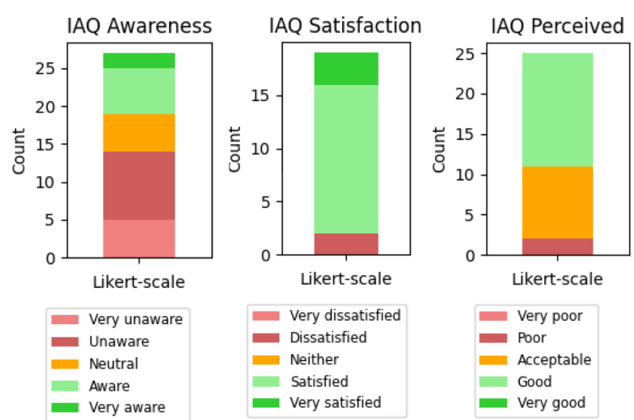


Figure 5: Likert-scales of IAQ awareness, perception and satisfaction of the questionnaire survey with occupant count

4.1.1 Activity and occupancy. The first set of questions of the survey focussed on activity and occupancy. On average, occupants who filled in the survey used the Lab42 building *3 times a week* for various activities (*f*=X). As opposed to 1 day a week, 4 days a week, 2 days a week with a small number of occupants using the building 5 days a week. Most occupants from the sample size were located on the *ground floor (f=X) and the first floor (f=X)* as opposed to the 2nd floor. Both the first floor and ground floor are considered the 'open area' and part of the atrium of the building. This is by design of the

[16] https://www.microsoft.com/nl-nl/microsoft-365
[17] https://atlasti.com/

building where the lower floors have more co-working spaces to be used as informal open learning spaces whereas the upper floors are more designed as meeting rooms and private working offices. Many occupants described the overall occupancy in the space as *not too crowded* (f=X) with a smaller percentage explicitly stating the space was crowded or not crowded at all.

4.1.2 Awareness, perceived and satisfaction. The second set of questions were three Likert scales about perceived IAQ, awareness of IAQ, and satisfaction with IAQ. Over half of the occupants are *not particularly aware* of the IAQ in their current space, either very unaware (f=X), unaware (f=X), or neutral (f=X) the minority of the occupants are aware or very aware. Indicating that in general occupants are not very aware of the IAQ if they are directly asked about it. However, once occupants are asked about their perceived IAQ and satisfaction the majority of the occupants perceive the IAQ as *acceptable (f=X) or good (f=X)* and almost all occupants consider the IAQ as satisfactory by being *satisfied (f=X) or very satisfied (f=X)* with the IAQ.

4.1.3 Health and cognitive symptons. The third set of questions were to indicate if users suffered from health or cognitive symptons based on the IAQ. The majority of participants answered *none* to both the health (f=X) and cognitive (f=X) questions. A small percentage experienced health symptoms such as headaches and feeling noiziating and a larger percentage experienced cognitive symptons such as trouble with focus or tiredness. The results of this section of the survey are inconclusive since it's difficult to determine if these symptons are specifically related to the air quality.

4.1.4 Open-ended air quality description. The most notable finding of the open question is that the occupants who filled in the not mandatory question describing their perception of IAQ mention specifically the openness of the atrium space:

P11: "[...] think it is good, [...] although I must say that this is mostly based on the large amount of open space in the building"

With some of the occupants mentioning the 'high ceilings' of the atrium specifically.

P8: " [...] feel like in this building the air quality is really good, mainly because of the impression the high ceilings give"

P13: "I like the air quality. This may also be because I sit close to the door and the ceiling is high."

Another notable attribute is that many occupants describe contributing to the perception that the IAQ is sufficient are the hanging planters and greenery that is present within the atrium.

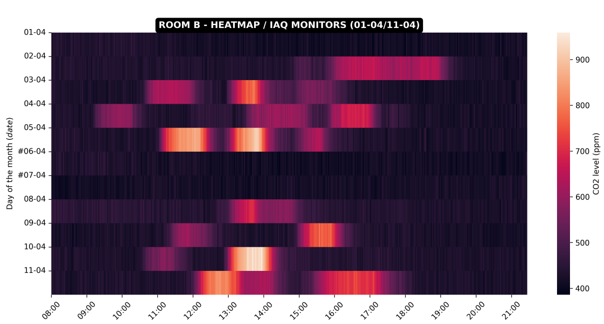
P16: "[..] I also see green plants around me, of which I think they are real."

P14: "[...] and the hanging plants that are present.

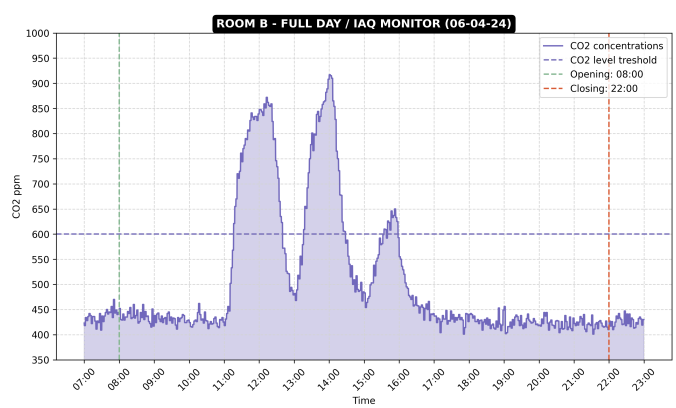
4.2 Air Quality Monitors

The gathered data logs are exported from the devices and analyzed with a focus on CO2 concentrations since this is the main IAQ parameter that influences air quality negatively within indoor environments based on occupancy within a room. Analyzation of the data logs shows occupancy patterns of a 'typical meeting', scheduled meeting patterns for the case study rooms and more notably the development of CO2 concentrations within both meeting rooms regularly where they regulary exceed optimal CO2 concentration tresholds above 600ppm.

4.2.1 Single meeting CO2 development. A sample of CO2 concentrations in a single meeting is shown in (see Figure 6). The lineplot shows the development of a 'regular' 1-hour meeting within the room. The plot are the CO2 concentrations over time in minutes with a x-axis line of 600ppm indicating the maximum 'ideal' treshold. Two coloured lines on the y-axis indicate the start and end time of the meeting. The observations show that after 15 minutes of the meeting started the CO2 concentrations reach suboptimal levels and continou to rise towards 950ppm level where it stabilizes as the 'maximum value' of the meeting. As stated before, continous exposure to CO2 concentrations especially between 800ppm - 1000ppm and even above are considered 'bad' and can impact cognitive functions. After ending of the meeting the concentrations slowly start to decrease to the baseline of 450ppm when occupants leave the meeting room at the end time.



(a) Heatmap of Room B with ten days of data collection



(b) Lineplot of Room B with a single day of meetings

Figure 4: Plots of the IAQ monitor data logs CO2 concentrations within the meeting rooms

4.2.2 Regular day CO2 development. The visualization (see Figure 6) shows the spikes of CO2 concentrations during a sample day where multiple meetings occured. Again, the x-axis plots the CO2 concentrations and this time the y-axis shows a full day with opening hours of the building. Based on similar plots of randomly sampled days the data shows most meetings occur between late in the morning (11:00) and usually end late in the afternoon (17:00) where after no more meetings are planned. That's roughly two hours after opening of the building and roughly four hours before closing of the building. There are outliers, on some days meeting occur early in the morning straight after opening time, and occassionaly a (longer) meeting that is longer and spans longer in the evening.

4.2.3 Meeting schedule CO2 development. A heatmap of ten days of CO2 concentration monitoring (see Figure 6) shows that it's common that two or three meetings occur on a single day and typically spans one hour. The majority of the meetings go beyond the 600ppm CO2 concentrations. Based on the lineplots and heatmaps it is assumed that the 'larger' Room B is more frequently used and reaches higher CO2 concentrations but those results are not definite since it heavily relies on context and the dates and time periods that spanned the data collection and the monitors were installed.

4.3 Prototype

Based on the requirements, data physicalization design principles, and concept models exploration a final high fidelity (hi-fi) version of the prototype was developed that functioned as a proof-of-concept of the physical design solution as a feasibility study and utilized in the user study for evaluation.

4.3.1 Concept description. *Bluebird* is a hanging kinetic type sculpture inspired by organic nature materials and the shapes of hanging planters that encode the environmental properties of indoor air quality data. It is meant to be hung from the ceiling in small to medium rooms and changes based on real-time air quality monitor data. Strings (plant branches) either become longer or smaller simulating the growth of a plant. Movements of the leaves indicate the freshness of air and movement. The overall design philosophy of the shapes and forms uses the notion of calm technology to minimize interruption cost [12].

4.3.2 Electronics and components. A controller device running on an Arduino Uno R3 [18] microcontroller with an MKR Motor shield is used [19] to control six 360° MG90S type Micro Servo Motors [20]. Attached to these motors are pulleys with fishing lines simulating the growth of the hanging planter so that the string can be moved up and down.

4.3.3 Crafting technologies and materials. The strings, leaves, and housings of the electronics and mechanical hardware are created using additive manufacturing (3D Printing) using a Fused deposition Modeling (FDM) technique using Polylactic acid (PLA) plastic filament in various colors. The electronics enclosures and plant models were modeled using computer-aided design (CAD) software. A digital fabrication technique commonly found in data physicalization prototypes [4]. To create leaves representing textile or fabric custom properties were defined within the 3D printing software (Slicing) to remove top and bottom layers and create a thin layer of infill.

4.3.4 System Architecture and software. The microcontroller uses custom firmware written in Arduino code [21] (similar to C++) that receives real-time data from the air quality monitors using the LoRaWAN [22] communication protocol to control the mechanics of the prototype (see Appendix K). This arrangement of hardware is commonly found in Internet of Things (IoT) architecture set-ups and follows the notion of Edge Computing with a (1) sensing, (2) networking, (3) processing, and (4) application layer [22, 33].

4.3.5 Experimental set-up. The prototype was hang-up at the two meeting rooms. Interaction set-up etc. Write about how the prototype is in the room. Installed (reference lab settings again). Reference figures in appendix for more photographs and impressions.

We derived five relevant dimensions based on the literature; *audience, intention, interaction, philosophy, representation* [21, 43].

4.3.6 Audience.

4.3.7 Intention.

4.3.8 Interaction.

4.3.9 Data representation. Write about data scale (stevens) nominal, ordinal and numerical. Needs electronic components (e.g. microcontrollers, sensors) and non-electronic components.

4.3.10 Design elements.

- **Sight**: visually see string become largers. Acts as a metaphor of plant 'growth'. The better the air quality the more the plant can 'grow'.
- **Movement**: if fresh air comes in we indicate this through movement as a metaphor for wind gusses between a field of grass or plants.

Figure 6: Bluebird prototype installed in the meeting room

[18] https://store.arduino.cc/products/arduino-uno-rev3
[19] https://store.arduino.cc/products/arduino-motor-shield-rev3
[20] https://www.towerpro.com.tw/product/mg90s-3/
[21] https://www.arduino.cc/reference/en/
[22] https://lora-alliance.org/about-lorawan/

4.4 Evaluation

The evaluation methods (see 3.2) are used to assess the quality and impact of the data physicalisation with a focus on how users perceive the data embedded in the physical representation and what long-term impact it has on people.

4.4.1 Understanding (learnability). Did users understand the phys? Know what it was visualizing? Users reaction?

4.4.2 Self-reflection (memorability). Makes you more aware of IAQ?

4.4.3 Effectiveness (efficiency). Suspected to change habits based on output? Attitude change? Behavioral stimulation.

5 DISCUSSION

5.1 Ethical considerations

5.2 Limitations

5.2.1 Validity.

5.2.2 Prototype scalability. Concessions were made during the creation of the prototype. Limitations in time, hardware availability and technical limitations. Design improvements are prevelent with the design of the prototype. The look and feel of a prototype can impact the effectiveness of the design as users perceive the design as a non-functioning prototyping. Usability tests and observations were done in natural settings which means participants have different contextual understandings of situations which can skew the interperation of the prototype within the lab setting (meaning in context). Also interviews as a methodology has inherent interviewee and researcher bias. Triangolution occured to minimize potential bias as much as possible.

5.2.3 Generalizability. Tested within the Lab42 building, so it's hard to test effectiveness are scalable to other (university) buildings. There are many environmental properties specific to this building (furniture, room allocation) that gives this context. There is inherent bias in the user group, although distribution of the surveys and interviews were voluntary and random (in terms of gender, role) geographics and location play a role. The case study building is a university building so it is expected that the data is biased towards higher-educated university students and staff members and not representative of a larger population. It is not clear if the results can be externally validated and generalized from sample size to larger population.

5.3 Future work

Future work, the prototype to communicate more sensory properties. We envision fabric that holds water to communicate humidity etc. made of organic materials etc.

6 CONCLUSION

Write your conclusion here. Be sure that the relation between the research gap and your contribution is clear. Be honest about how limitations in the study qualify the answer on the research question.

REFERENCES

[1] Hamed S. Alavi, Elizabeth F. Churchill, Mikael Wiberg, Denis Lalanne, Peter Dalsgaard, Ava Fatah gen Schieck, and Yvonne Rogers. 2019. Introduction to Human-Building Interaction (HBI): Interfacing HCI with Architecture and Urban Design. *ACM Transactions on Computer-Human Interaction* 26, 2 (March 2019), 6:1–6:10. https://doi.org/10.1145/3309714

[2] Hamed S. Alavi, Himanshu Verma, Michael Papinutto, and Denis Lalanne. 2017. Comfort: A Coordinate of User Experience in Interactive Built Environments. In *Human-Computer Interaction – INTERACT 2017 (Lecture Notes in Computer Science)*, Regina Bernhaupt, Girish Dalvi, Anirudha Joshi, Devanuj K. Balkrishan, Jacki O'Neill, and Marco Winckler (Eds.). Springer International Publishing, Cham, 247–257. https://doi.org/10.1007/978-3-319-67687-6_16

[3] Jason Alexander, Petra Isenberg, Yvonne Jansen, Bernice E. Rogowitz, and Andrew Vande Moere. 2019. Data Physicalization. *Dagstuhl Reports* 8, 10 (April 2019), 127. https://doi.org/10.4230/DagRep.8.10.127

[4] Anhalt University, Germany and Žarko Dumičić. 2022. Design elements in data physicalization: A systematic literature review. https://doi.org/10.21606/drs.2022.660

[5] Architectenweb. 2022. LAB42, Faculteitsgebouw Uva Science Park. https://architectenweb.nl/p44033 *Last accessed: 2024-03-25*.

[6] Benthem Crouwel Architects. 2022. LAB42 - Project case study. https://www.benthemcrouwel.com/projects/lab42 *Last accessed: 2024-03-25*.

[7] Patrick Bader, Alexandra Voit, Huy Viet Le, Paweł W. Woźniak, Niels Henze, and Albrecht Schmidt. 2019. WindowWall: Towards Adaptive Buildings with Interactive Windows as Ubiquitous Displays. *ACM Transactions on Computer-Human Interaction* 26, 2 (March 2019), 11:1–11:42. https://doi.org/10.1145/3310275

[8] S. Sandra Bae, Clement Zheng, Mary Etta West, Ellen Yi-Luen Do, Samuel Huron, and Danielle Albers Szafir. 2022. Making Data Tangible: A Cross-disciplinary Design Space for Data Physicalization. https://doi.org/10.48550/arXiv.2202.10520 arXiv:2202.10520 [cs].

[9] Genevieve Bell and Paul Dourish. 2007. Yesterday's tomorrows: notes on ubiquitous computing's dominant vision. *Personal and Ubiquitous Computing* 11, 2 (Jan. 2007), 133–143. https://doi.org/10.1007/s00779-006-0071-x

[10] Alexandra Boissonneault and Terri Peters. 2023. Concepts of performance in post-occupancy evaluation post-probe: a literature review. *Building Research & Information* 51, 4 (May 2023), 369–391. https://doi.org/10.1080/09613218.2022.2132906 Publisher: Routledge _eprint: https://doi.org/10.1080/09613218.2022.2132906.

[11] John Brooke. 1996. *SUS – a quick and dirty usability scale.* 189–194.

[12] Amber Case. 2016. *Calm Technology: Principles and Patterns for Non-Intrusive Design* (1st edition ed.). O'Reilly Media, Beijing.

[13] Ylona Chun Tie, Melanie Birks, and Karen Francis. 2019. Grounded theory research: A design framework for novice researchers. *SAGE Open Medicine* 7 (Jan. 2019), 2050312118822927. https://doi.org/10.1177/2050312118822927

[14] R. V. Corlan, R. M. Balogh, I. Ionel, and St Kilyeny. 2021. The importance of indoor air quality (IAC) monitoring. *Journal of Physics: Conference Series* 1781, 1 (Feb. 2021), 012062. https://doi.org/10.1088/1742-6596/1781/1/012062 Publisher: IOP Publishing.

[15] Fred D. Davis. 1989. Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. *MIS Quarterly* 13, 3 (1989), 319–340. https://doi.org/10.2307/249008 Publisher: Management Information Systems Research Center, University of Minnesota.

[16] Pierre Dragicevic, Yvonne Jansen, and Andrew Vande Moere. 2020. Data Physicalization. In *Handbook of Human Computer Interaction*, Jean Vanderdonckt, Philippe Palanque, and Marco Winckler (Eds.). Springer International Publishing, Cham, 1–51. https://doi.org/10.1007/978-3-319-27648-9_94-1

[17] Bowen Du, Marlie C. Tandoc, Michael L. Mack, and Jeffrey A. Siegel. 2020. Indoor CO2 concentrations and cognitive function: A critical review. *Indoor Air* 30, 6 (2020), 1067–1082. https://doi.org/10.1111/ina.12706 _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/ina.12706.

[18] Mohamed Elsayed, Sofie Pelsmakers, Lorenza Pistore, Raúl Castaño-Rosa, and Piercarlo Romagnoni. 2023. Post-occupancy evaluation in residential buildings: A systematic literature review of current practices in the EU. *Building and Environment* 236 (May 2023), 110307. https://doi.org/10.1016/j.buildenv.2023.110307

[19] Hermann Fromme. 2023. Indoor Environment: Background Information. In *Indoor Air Quality: Occurrence and Health Effects of Contaminants*, Hermann Fromme (Ed.). Springer Nature Switzerland, Cham, 1–36. https://doi.org/10.1007/978-3-031-40078-0_1

[20] Sonal Gawande, Rajnarayan Tiwari, Prakash Narayanan, and Ashwin Bhadri. 2020. Indoor air quality and sick building syndrome: Are green buildings better than conventional buildings? *Indian Journal of Occupational and Environmental Medicine* 24, 1 (Jan. 2020), 30–30. https://go-gale-com.proxy.uba.uva.nl/ps/i.do?p=AONE&sw=w&issn=09732284&v=2.1&it=r&id=GALE%7CA618547062&sid=googleScholar&linkaccess=abs Publisher: Indian Association of Occupational Health.

[21] Eva Hornecker, Trevor Hogan, Uta Hinrichs, and Rosa Van Koningsbruggen. 2023. A Design Vocabulary for Data Physicalization. *ACM Transactions on Computer-Human Interaction* 31, 1 (Nov. 2023), 2:1–2:62. https://doi.org/10.1145/3617366

[22] Zeba Idrees, Zhuo Zou, and Lirong Zheng. 2018. Edge Computing Based IoT Architecture for Low Cost Air Pollution Monitoring Systems: A Comprehensive System Analysis, Design Considerations & Development. *Sensors* 18, 9 (Sept. 2018), 3021. https://doi.org/10.3390/s18093021 Number: 9 Publisher: Multidisciplinary Digital Publishing Institute.

[23] Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. 2013. Evaluating the efficiency of physical visualizations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, Paris France, 2593–2602. https://doi.org/10.1145/2470654.2481359

[24] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. 2015. Opportunities and Challenges for Data Physicalization. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. Association for Computing Machinery, New York, NY, USA, 3227–3236. https://doi.org/10.1145/2702123.2702180

[25] Stine Schmieg Johansen, Jesper Kjeldskov, and Mikael B. Skov. 2019. Temporal Constraints in Human–Building Interaction. *ACM Transactions on Computer-Human Interaction* 26, 2 (April 2019), 8:1–8:29. https://doi.org/10.1145/3301424

[26] Jonathan Lazar, Jinjuan Heidi Feng, and Harry Hochheiser. 2017. *Research Methods in Human-Computer Interaction*. Vol. Second edition. Morgan Kaufmann, Cambridge, MA. https://search.ebscohost.com/login.aspx?direct=true&db=e000xww&AN=1158797&site=ehost-live&scope=site

[27] Hakpyeong Kim, Taehoon Hong, and Jimin Kim. 2019. Automatic ventilation control algorithm considering the indoor environmental quality factors and occupant ventilation behavior using a logistic regression model. *Building and Environment* 153 (April 2019), 46–59. https://doi.org/10.1016/j.buildenv.2019.02.032

[28] Jimin Kim, Taehoon Hong, Minhyun Lee, and Kwangbok Jeong. 2019. Analyzing the real-time indoor environmental quality factors considering the influence of the building occupants' behaviors and the ventilation. *Building and Environment* 156 (June 2019), 99–109. https://doi.org/10.1016/j.buildenv.2019.04.003

[29] David Kirsh. 2019. Do Architects and Designers Think about Interactivity Differently? *ACM Transactions on Computer-Human Interaction* 26, 2 (April 2019), 7:1–7:43. https://doi.org/10.1145/3301425

[30] Neil E. Klepeis, William C. Nelson, Wayne R. Ott, John P. Robinson, Andy M. Tsang, Paul Switzer, Joseph V. Behar, Stephen C. Hern, and William H. Engelmann. 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Science & Environmental Epidemiology* 11, 3 (July 2001), 231–252. https://doi.org/10.1038/sj.jea.7500165 Publisher: Nature Publishing Group.

[31] Priyanka Kulshreshtha, Sumanth Chinthala, Prashant Kumar, and Barun Aggarwal (Eds.). 2024. *Indoor Environmental Quality: Select Proceedings of ACIEQ 2023*. Lecture Notes in Civil Engineering, Vol. 380. Springer Nature, Singapore. https://doi.org/10.1007/978-981-99-4681-5

[32] Jared Langevin, Jin Wen, and Patrick L. Gurian. 2016. Quantifying the human–building interaction: Considering the active, adaptive occupant in building performance simulation. *Energy and Buildings* 117 (April 2016), 372–386. https://doi.org/10.1016/j.enbuild.2015.09.026

[33] Chao Li, Yushu Xue, Jing Wang, Weigong Zhang, and Tao Li. 2019. Edge-Oriented Computing Paradigms: A Survey on Architecture Design and System Management. *Comput. Surveys* 51, 2 (March 2019), 1–34. https://doi.org/10.1145/3154815

[34] Eleni Margariti, Vasilis Vlachokyriakos, and David Kirk. 2023. Understanding occupants' experiences in quantified buildings: results from a series of exploratory studies.. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3544548.3581256

[35] Nielsen Norman Group (NN/g). 2024. UX and Usability Articles from Nielsen Norman Group - Topic Research Methods, User Testing & Usability Heuristics. https://www.nngroup.com/articles/ *Last accessed: 2024-04-17.*

[36] Jovan Pantelic, Negin Nazarian, Clayton Miller, Forrest Meggers, Jason Kai Wei Lee, and Dusan Licina. 2022. Transformational IoT sensing for air pollution and thermal exposures. *Frontiers in Built Environment* 8 (Oct. 2022). https://doi.org/10.3389/fbuil.2022.971523 Publisher: Frontiers.

[37] Guiseppe Ryan Passarelli. 2009. Sick building syndrome: An overview to raise awareness. *Journal of Building Appraisal* 5, 1 (July 2009), 55–66. https://doi.org/10.1057/jba.2009.20

[38] Andrew Persily. 2015. Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62. *Building and Environment* 91 (Sept. 2015), 61–69. https://doi.org/10.1016/j.buildenv.2015.02.026

[39] Andrew Pulsipher and Michail Giannakos. 2023. Towards a Taxonomy of Human-Building Interactions. In *Adjunct Proceedings of the 2023 ACM International Joint Conference on Pervasive and Ubiquitous Computing & the 2023 ACM International Symposium on Wearable Computing (UbiComp/ISWC '23 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 411–416. https://doi.org/10.1145/3594739.3610730

[40] Champika Ranasinghe and Auriol Degbelo. 2023. Encoding Variables, Evaluation Criteria, and Evaluation Methods for Data Physicalisations: A Review. *Multimodal Technologies and Interaction* 7, 7 (July 2023), 73. https://doi.org/10.3390/mti7070073 Number: 7 Publisher: Multidisciplinary Digital Publishing Institute.

[41] Yvonne Rogers, William R. Hazlewood, Paul Marshall, Nick Dalton, and Susanna Hertrich. 2010. Ambient influence: can twinkly lights lure and abstract representations trigger behavioral change?. In *Proceedings of the 12th ACM international conference on Ubiquitous computing (UbiComp '10)*. Association for Computing Machinery, New York, NY, USA, 261–270. https://doi.org/10.1145/1864349.1864372

[42] Yvonne Rogers and Paul Marshall. 2017. Moving Into The Wild: From Situated Cognition to Embodied Interaction. In *Research in the Wild*, Yvonne Rogers and Paul Marshall (Eds.). Springer International Publishing, Cham, 11–20. https://doi.org/10.1007/978-3-031-02220-3_2

[43] Kim Sauvé, Miriam Sturdee, and Steven Houben. 2022. Physecology: A Conceptual Framework to Describe Data Physicalizations in their Real-World Context. *ACM Transactions on Computer-Human Interaction* 29, 3 (Jan. 2022), 27:1–27:33. https://doi.org/10.1145/3505590

[44] Holger Schnädelbach, Nils Jäger, and Lachlan Urquhart. 2019. Adaptive Architecture and Personal Data. *ACM Transactions on Computer-Human Interaction* 26, 2 (March 2019), 12:1–12:31. https://doi.org/10.1145/3301426

[45] Christian Schweizer, Rufus David Edwards, Lucy Bayer-Oglesby, William James Gauderman, Vito Ilacqua, Matti Juhani Jantunen, Hak Kan Lai, Mark Nieuwenhuijsen, and Nino Künzli. 2007. Indoor time-microenvironment-activity patterns in seven regions of Europe. *Journal of Exposure Science & Environmental Epidemiology* 17, 2 (March 2007), 170–181. https://doi.org/10.1038/sj.jes.7500490

[46] Marielle Ferreira Silva, Stefan Maas, Henor Artur de Souza, and Adriano Pinto Gomes. 2017. Post-occupancy evaluation of residential buildings in Luxembourg with centralized and decentralized ventilation systems, focusing on indoor air quality (IAQ). Assessment by questionnaires and physical measurements. *Energy and Buildings* 148 (Aug. 2017), 119–127. https://doi.org/10.1016/j.enbuild.2017.04.049

[47] Young Joo Son, Zachary C. Pope, and Jovan Pantelic. 2023. Perceived air quality and satisfaction during implementation of an automated indoor air quality monitoring and control system. *Building and Environment* 243 (Sept. 2023), 110713. https://doi.org/10.1016/j.buildenv.2023.110713

[48] Ricardo Sosa, Victoria Gerrard, Antonio Esparza, Rebeca Torres, and Robbie Napper. 2018. Data Objects: Design Principles for Data Physicalisation. 1685–1696. https://doi.org/10.21278/idc.2018.0125

[49] Holly Sowles and Laura Huisinga. 2021. Introducing Intelligent Interior Design Framework (IIDF) and the Overlap with Human Building Interaction (HBI). In *Advances in Artificial Intelligence, Software and Systems Engineering (Advances in Intelligent Systems and Computing)*, Tareq Ahram (Ed.). Springer International Publishing, Cham, 483–489. https://doi.org/10.1007/978-3-030-51328-3_66

[50] Steph Menken and Machiel Keestra. 2016. *An Introduction to Interdisciplinary Research : Theory and Practice*. Amsterdam University Press, Amsterdam. https://search.ebscohost.com/login.aspx?direct=true&db=e000xww&AN=1212825&site=ehost-live&scope=site Issue: volume 2.

[51] Simon Stusak, Jeannette Schwarz, and Andreas Butz. 2015. Evaluating the Memorability of Physical Visualizations. https://doi.org/10.1145/2702123.2702248

[52] Roohollah Taherkhani and Mohamadmahdi Aziminezhad. 2023. Human-building interaction: A bibliometric review. *Building and Environment* 242 (Aug. 2023), 110493. https://doi.org/10.1016/j.buildenv.2023.110493

[53] Himanshu Verma, Hamed S. Alavi, and Denis Lalanne. 2017. Studying Space Use: Bringing HCI Tools to Architectural Projects. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 3856–3866. https://doi.org/10.1145/3025453.3026055

[54] Chao Wang, Fan Zhang, Julian Wang, James K. Doyle, Peter A. Hancock, Cheuk Ming Mak, and Shichao Liu. 2021. How indoor environmental quality affects occupants' cognitive functions: A systematic review. *Building and Environment* 193 (April 2021), 107647. https://doi.org/10.1016/j.buildenv.2021.107647

[55] Yun Wang, Adrien Segal, Roberta Klatzky, Daniel F. Keefe, Petra Isenberg, Jorn Hurtienne, Eva Hornecker, Tim Dwyer, and Stephen Barrass. 2019. An Emotional Response to the Value of Visualization. *IEEE Computer Graphics and Applications* 39, 5 (Sept. 2019), 8–17. https://doi.org/10.1109/MCG.2019.2923483

[56] Mark Weiser. 1999. The computer for the 21 st century. *ACM SIGMOBILE Mobile Computing and Communications Review* 3, 3 (July 1999), 3–11. https://doi.org/10.1145/329124.329126

[57] Sailin Zhong, Denis Lalanne, and Hamed Alavi. 2021. The Complexity of Indoor Air Quality Forecasting and the Simplicity of Interacting with It – A Case Study of 1007 Office Meetings. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–19. https://doi.org/10.1145/3411764.3445524

[58] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. 2007. Research through design as a method for interaction design research in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. Association for Computing Machinery, New York, NY, USA, 493–502. https://doi.org/10.

1145/1240624.1240704

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Appendix B ETHICAL CONSIDERATIONS

Before user studies and data gathering were conducted, an application to the Ethics Committee for Information Sciences (ECIS) [23] was made. No ethical issues were raised and the committee gave positive advice before the start of the research. All individuals participating in the questionnaire and evaluation process were obliged to confirm their voluntary involvement by carefully reading and submitting consent forms, with the assurance that they retained the right to withdraw from participation at any point without the need for explanation.

Participants were informed about the goal of the study and the structure of the interviews. To uphold confidentiality and privacy, questionnaire participation occurred anonymously, and all evaluation interview data underwent anonymization following the conclusion of the evaluation sessions. Interacting with occupants within the building and interacting with participants of the usability tests of the prototype adhered to the principles outlined in the University of Amsterdam Code of Conduct [24] and Campus rules and Policies [25].

Appendix C DOMAIN EXPERT VALIDITY

Before conducting the questionnaire, data gathering process, and interview evaluation procedures, domain experts from the Informatics Institute [26] and the Digital Interactions Lab (DIL) [27] at the University of Amsterdam reviewed the methodology procedures. Draft versions of the questions and techniques were sent out to staff and supervisors for feedback internally. The questionnaire and interview procedure were pilot-tested internally. After several iterations then more widely distributed to occupants and opened for participation.

Appendix D DATA STORAGE AND ARCHIVAL

During the research phase data collection methods, storage, and archival followed the Central guidelines for research data management (RDM) [28] from the University of Amsterdam. All occupant data was anonymized before publishing and nothing that can be considered personal data is collected. Data is stored on cloud service providers provided by the University of Amsterdam such as Research Drive [29]. Only the principal researcher and supervisor(s) in possession of the encryption methods and passwords can view the unstructured exported data from the questionnaires, monitoring devices, and interviews. Only aggregated datasets and data outputs for the purpose of visualization are published and can be publicly viewed.

Appendix E SOURCE CODE AND DATASETS

In the spirit of Open Access Research [30], to support reproducibility, mitigate a lack of transparency, and enable future work in this research field the aggregated datasets, notebooks, and prototype source code in this research are publicly available on a GitHub organization with the working title 'viszlab' [31] using the MIT License. Several code repositories for different parts of the research can be accessed and publicly viewed. The README file of each repository describes the contents and how to perform the technical set-up. Notable repositories are:

(1) **Prototype**. Arduino Code, component diagrams, and 3D models for the physical prototype.
https://github.com/viszlab/prototype
(2) **Datasets**. Python code and notebooks for data analysis of the questionnaire, monitor devices, and evaluation.
https://github.com/viszlab/prototype
(3) **Website**. One-pager website where all outputs such as this paper and photographs of the research can be downloaded.
https://github.com/viszlab/viszlab.github.io

[23] https://ivi.uva.nl/research/ethical-code/ethical-code.html
[24] https://www.uva.nl/en/about-the-uva/policy-and-regulations/
[25] https://extranet.uva.nl/en/content/a-z/house-rules-and-code-of-conduct/house-rules-and-code-of-conduct.html
[26] https://ivi.uva.nl/
[27] https://uva-dilab.com/
[28] https://rdm.uva.nl/en/introduction/rdm-introduction.html
[29] https://rdm.uva.nl/en/looking-after/storage/storage.html
[30] https://uba.uva.nl/en/support/research/open-access/open-access.html
[31] https://github.com/viszlab

Appendix F FLOORPLAN AND LAB SET-UP

A diagram providing an overview of the technical lab-setup of the IAQ monitors

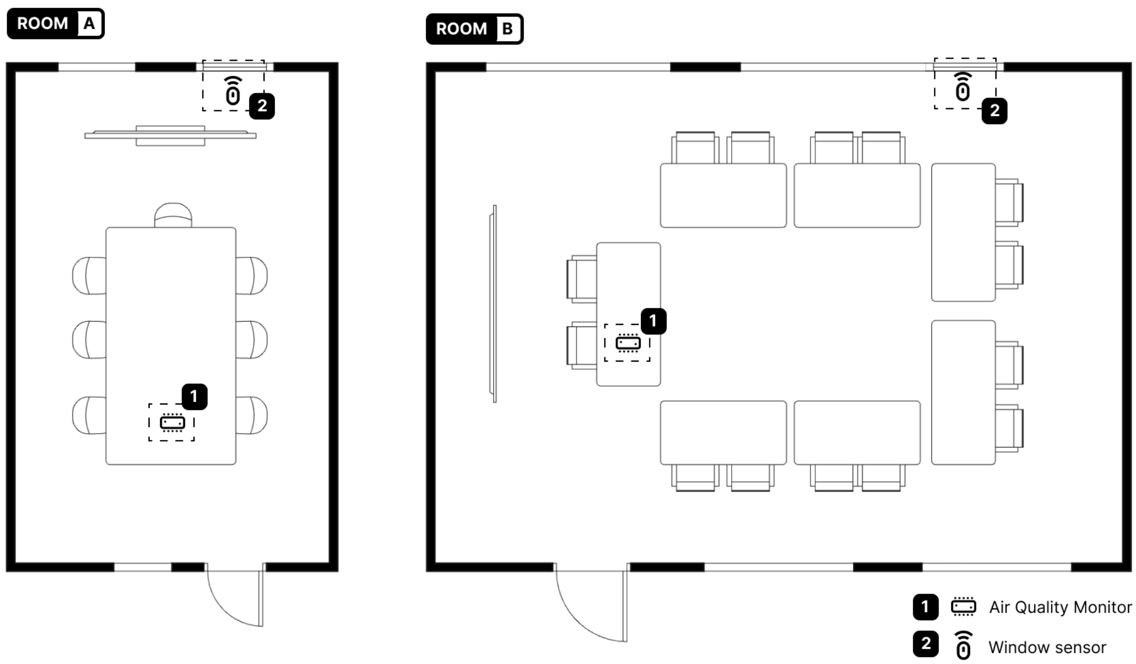


Figure 7: Floorplan of Room A and B with the position of the monitor devices installed to manufacturer specifications

Appendix G MEETING ROOM IMPRESSIONS

Photographs of the meeting rooms used for the lab-setup.

Figure 8: The 'smaller'($m2$) space labeled Room A

Figure 9: The 'larger' ($m2$) space labeled Room B

Appendix H BUILDING IMPRESSIONS

(a) first

(b) second

(c) third

(d) fourth

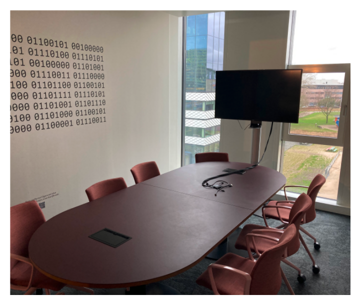
Figure 10: caption

Figure 11: System diagram that shows the

Appendix I PROTOTYPE IMPRESSIONS

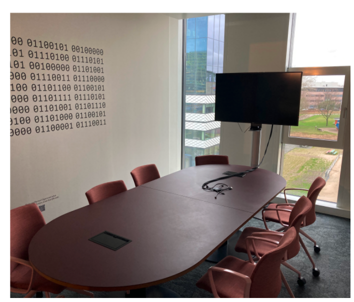
Figure 12: System diagram that shows the

(a) first



(b) second

(c) third



(d) fourth

Figure 13: caption

Appendix J IOT ARCHITECTURE OF THE PROTOTYPE

System diagram which shows the IoT architecture of the prototype.

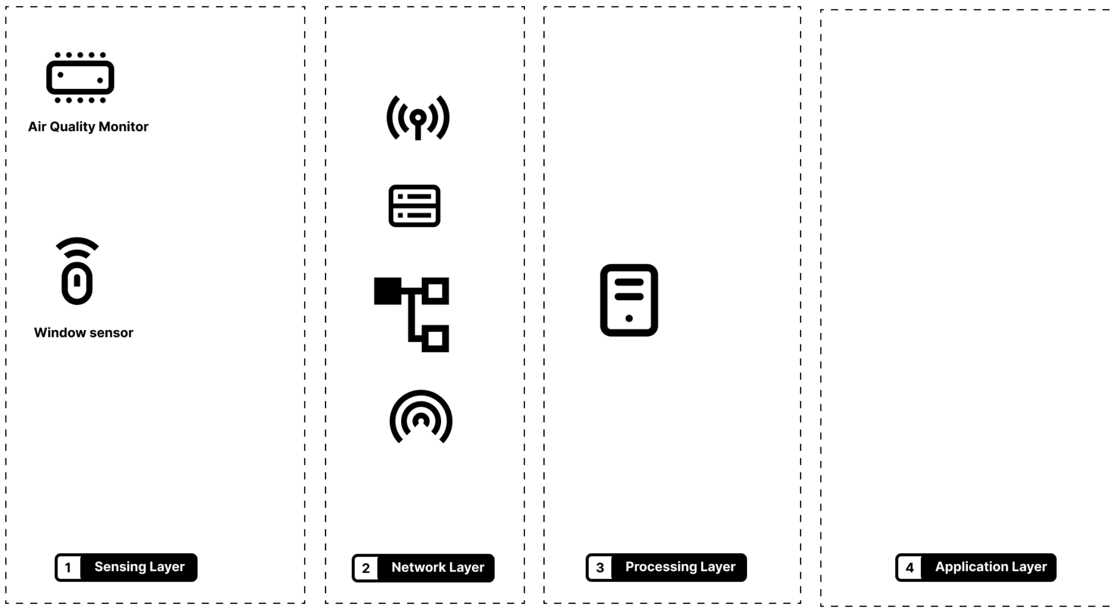


Figure 14: System diagram that shows the technical set-up of the prototype

Appendix K EXISTING BUILDING API SAMPLE DATA

Overview of the current building API with outputs.

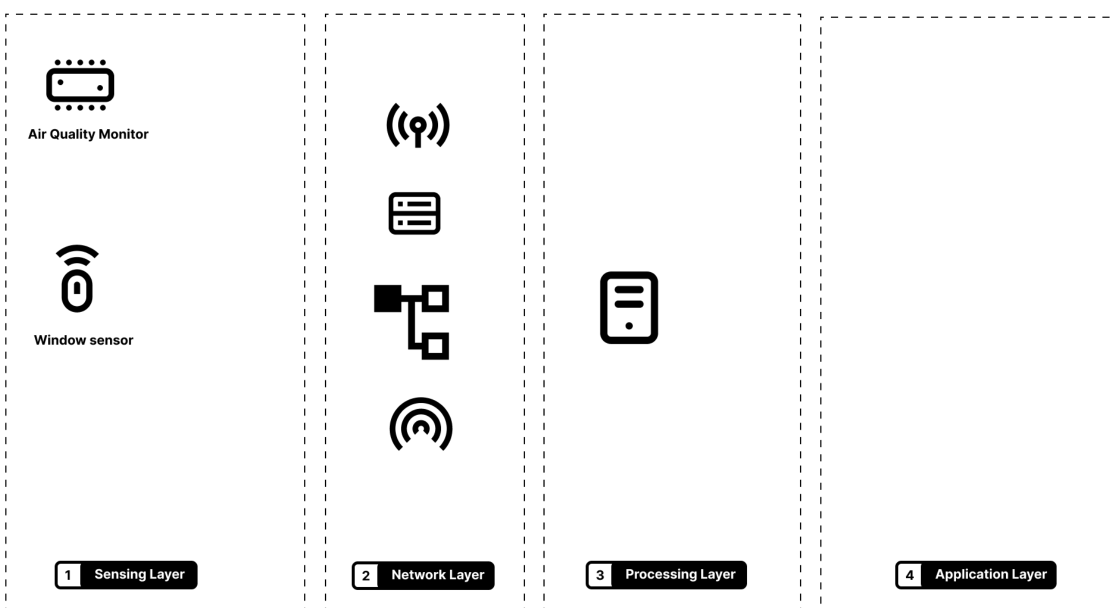


Figure 15: System diagram that shows the technical set-up of the prototype

Appendix L AIR QUALITY MONITORS SAMPLE DATA

Sample data log of the monitor devices.

Date	Time	CO2	Temp	RH	PM1.0	PM2.5	PM10	TVOC	BP	O3
2024/04/03	10:30	647	21'C	39%	0	0	0	255	99.97	0
2024/04/03	10:29	641	21'C	39%	0	0	0	249	99.97	0
2024/04/03	10:28	633	21'C	39%	0	0	0	246	99.97	0
2024/04/03	10:27	635	21'C	39%	1	1	1	242	99.97	0
2024/04/03	10:26	632	21'C	39%	0	1	1	237	99.97	0
2024/04/03	10:25	628	21'C	39%	0	1	1	236	99.97	0
2024/04/03	10:24	617	21'C	39%	0	1	1	232	99.97	0
2024/04/03	10:23	602	21'C	39%	0	1	1	232	99.97	0
2024/04/03	10:22	598	21'C	39%	0	0	0	231	99.97	0
2024/04/03	10:21	591	21'C	39%	0	1	1	228	99.97	0
2024/04/03	10:20	587	21'C	39%	0	0	0	228	99.97	0
2024/04/03	10:19	580	21'C	39%	0	0	0	230	99.97	0
2024/04/03	10:18	580	21'C	39%	0	0	0	232	99.97	0
2024/04/03	10:17	578	21'C	39%	1	1	1	234	99.97	0
2024/04/03	10:16	574	21'C	39%	0	0	0	237	99.97	0
2024/04/03	10:15	569	21'C	39%	0	0	0	237	99.97	0

Table 2: Sample data log of the Aircheq Touch Aero installed in the 'small' Room A

Date	Time	Temp	RH	DewPoint	CO2	-	-	-	-	-
10/04/2024	14:17:00	21.019	30.780	3.176	871.000					
10/04/2024	14:18:00	21.039	30.573	3.098	871.000					
10/04/2024	14:19:00	21.019	30.365	2.985	827.000					
10/04/2024	14:20:00	21.049	30.164	2.917	808.000					
10/04/2024	14:21:00	21.059	29.895	2.838	808.000					
10/04/2024	14:22:00	21.059	29.852	2.772	773.000					
10/04/2024	14:23:00	21.059	29.730	2.723	773.000					
10/04/2024	14:24:00	21.079	29.608	2.665	773.000					
10/04/2024	14:25:00	21.059	29.486	2.607	721.000					
10/04/2024	14:26:00	21.059	29.303	2.520	714.000					
10/04/2024	14:27:00	21.049	29.242	2.482	714.000					
10/04/2024	14:28:00	21.079	29.181	2.479	714.000					
10/04/2024	14:29:00	21.059	29.016	2.400	681.000					
10/04/2024	14:30:00	21.089	28.912	2.358	681.000					

Table 3: Sample data log of the Atal ATU-CT ClimaTrend installed in the 'large' Room B

Appendix M QUESTIONNAIRE SURVEY (POE)

Exported text version of the questionnaire survey created in Qualtrics and distributed using handouts on QR codes.

Introduction: *Hi! We at the Digital Interactions Lab (DIL) are researching indoor environments, focusing on Indoor Air Quality (IAQ) within smart buildings like Lab42, for a Master Thesis. This survey takes an average of ~3 minutes to complete and comprises questions about your overall comfort and awareness of Indoor Air Quality (IAQ).*

Informed Consent: *The survey is anonymous and collects data on environmental experiences and approximate building location for future research and publication. Participation is voluntary, and if you decide that you do not want to participate after you have completed it, please contact us. Principal researcher: BSc D. de Vries - danny.de.vries@student.uva.nl Supervisor(s): Shruti Rao PhD Candidate - s.rao@uva.nl Supervisor(s): Dr. H. Seiied Alavi PhD - ha.alavi@uva.nl Thank you for your valuable time and for participating in our survey!*

Q1: Location- Where are you currently located within the Lab42 building? *Multiple-choice, one option possible*

- On the ground floor (the atrium)
- On the first floor (1st floor - in a working space)
- On the second floor (2nd floor - in a working space)

Q2: Activity - On average, how often do you use Lab42 per week for various activities? *Multiple-choice, one option possible*

- 1 day a week
- 2 days a week
- 3 days a week
- 4 days a week
- 5 days a week

Q3: Occupancy - How would you describe the occupancy in your current space? *Multiple-choice, one option possible*

- Not crowded
- Not too crowded
- Crowded
- Very crowded
- At capacity

Q4: Awareness Air Quality - Did you know that poor air quality has been identified to pose health risks and affect cognitive performance? How aware are you of the current air quality in this space? *Likert-scale, one option possible*
1) Very Unaware **2)** Unaware **3)** Neutral **4)** Aware **5)** Very Aware

Q6: Perceived Air Quality - How do you perceive the air quality in the current space? *Likert-scale, one option possible*
1) Very Poor **2)** Poor **3)** Acceptable **4)** Good **5)** Very Good

Q7: Satisfaction Air Quality - How satisfied are you with the air quality in the current space? *Likert-scale, one option possible*
1) Very Dissatisfied **2)** Dissastisfied **3)** Neither dissatisfied or satisfied **4)** Satisfied **5)** Very Satisfied

Q8: Not mandatory - Would you like to describe in more detail in your own words how you currently feel about the Indoor Air Quality? *Open-question, insert text*

Q9: Health symptoms - Do you experience any health-related symptoms based on the air quality in this space? *Multiple-choice, multiple options possible, insert text field*

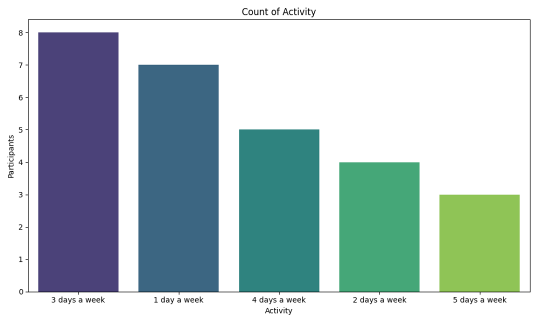
- None
- Headaches
- Trouble breathing
- Feeling nauseating
- Other

Q10: Cognitive symptoms - Do you experience any cognitive-based symptoms on the air quality in this space? *Multiple-choice, multiple options possible, insert text field*

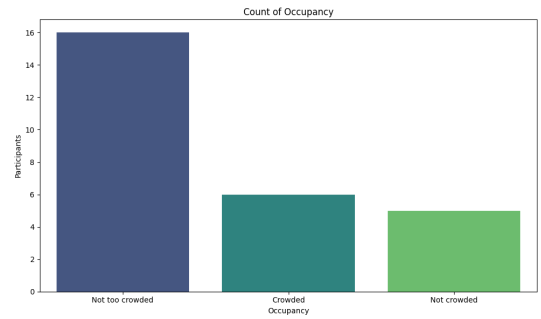
- None
- Trouble with focus
- Decreased productivity
- Tiredness
- Other

Appendix N SURVEY DATA

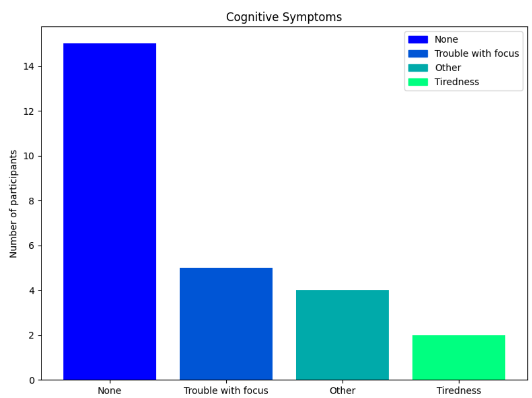
Plots of the results of the survey data exported from Qualtrics.



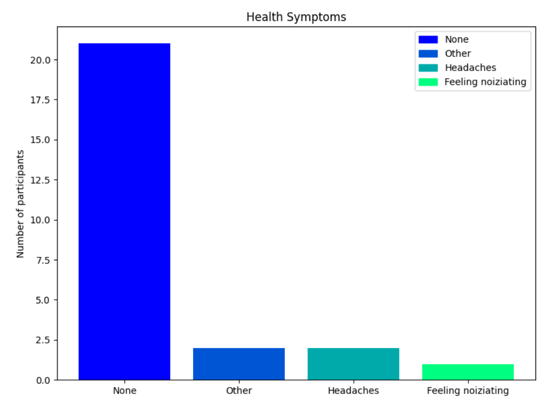
(a) Average use of the building for various activities



(b) Description of occupancy crowdedness

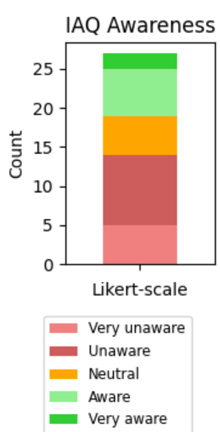


(c) Cognitive symptons based on the air quality

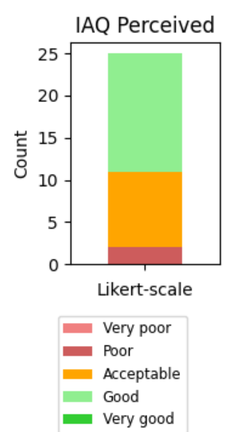


(d) Health symptons based on the air quality

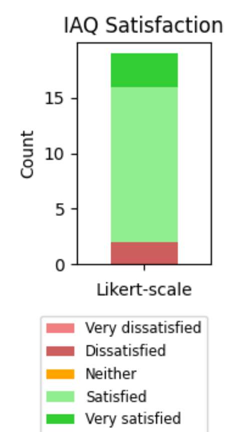
Figure 16: Bar charts of the survey questions about activity, occupancy, health and cognitive symptons



(a) Awaneress



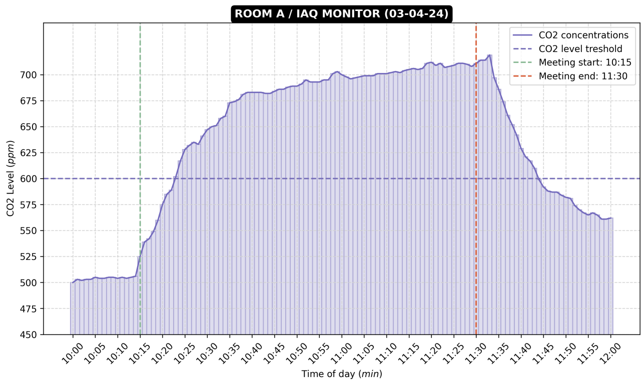
(b) Perceived



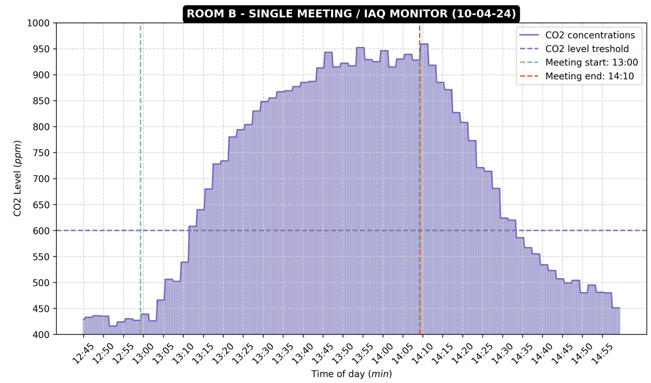
(c) Satisfaction

Figure 17: Stacked bar charts of the Likert-scales on IAQ awareness, perceived and satisfaction

Appendix O MONITOR DATA

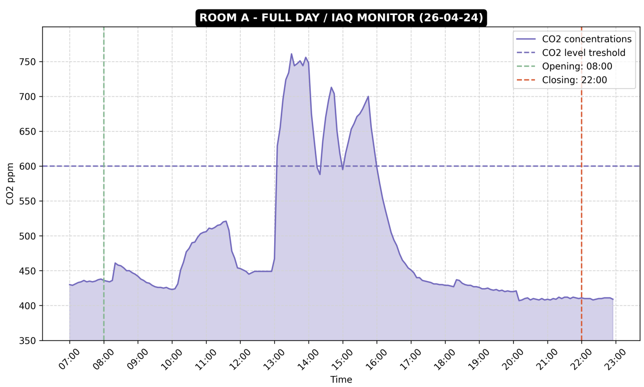


(a) Single meeting CO2 concentrations in Room A

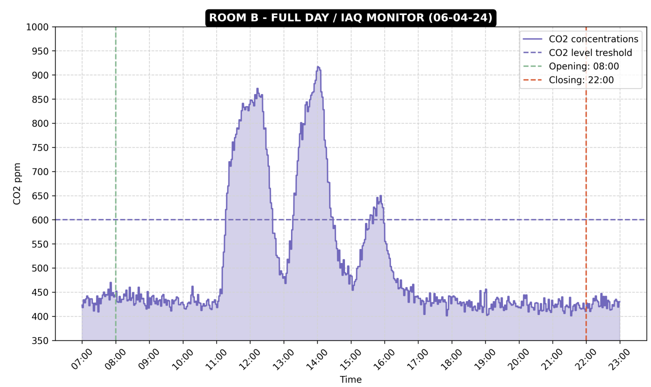


(b) Single meeting CO2 concentrations in Room B

Figure 18: IAQ monitoring CO2 concentrations of a single sample meeting based on the start and end time of the meeting

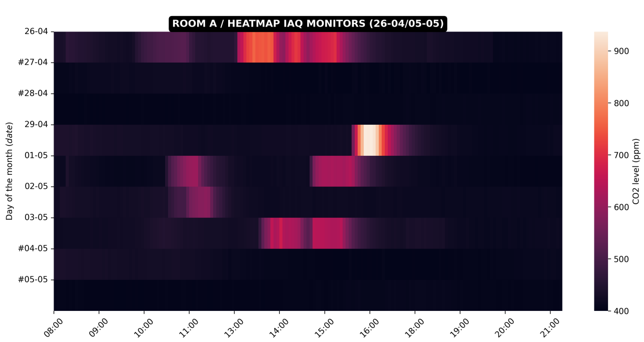


(a) A day of meetings CO2 concentrations in Room A

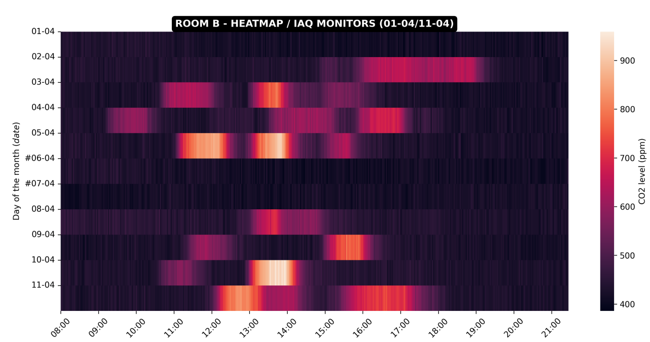


(b) A day of meetings CO2 concentrations in Room B

Figure 19: IAQ monitoring CO2 concentrations of a sample day meeting based on the opening hours of the building



(a) Heatmap of ten days of monitoring in Room A



(b) Heatmap of ten days of monitoring in Room B

Figure 20: IAQ monitoring heatmap CO2 concentrations of the sample ten days based on the opening hours of the building

Appendix P EVALUATION INTERVIEWS

Appendix Q USABILITY TESTS

Appendix R EFFECTIVENESS SCORES

Appendix S CONCEPT DIAGRAMS

Design diagrams of the brainstormed concepts in medium-fi sketches that show the component breakdown and interaction states.

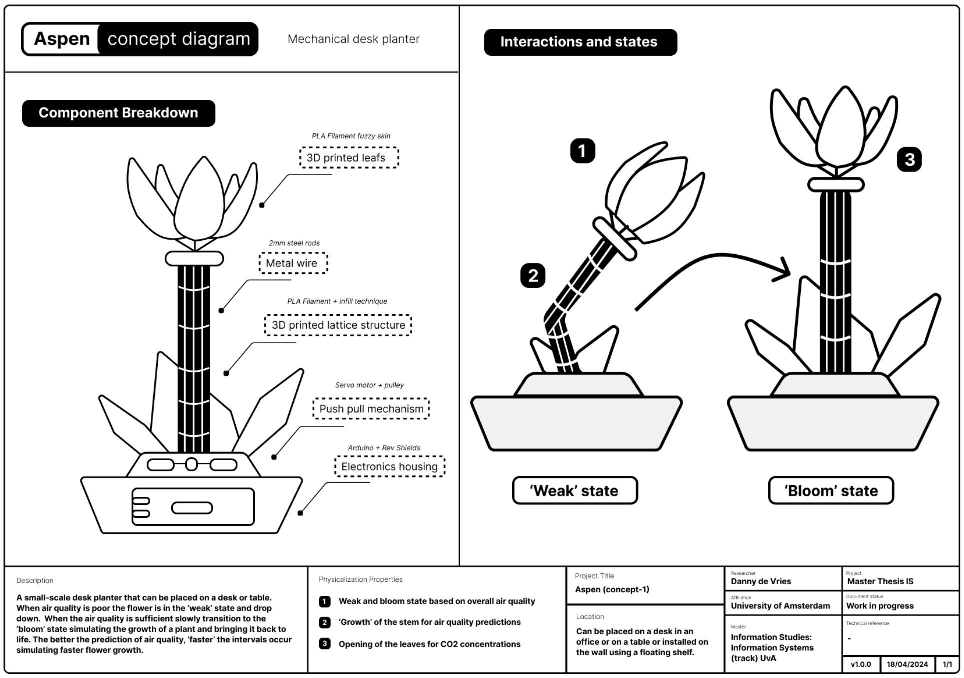


Figure 21: Design diagram of Concept-2

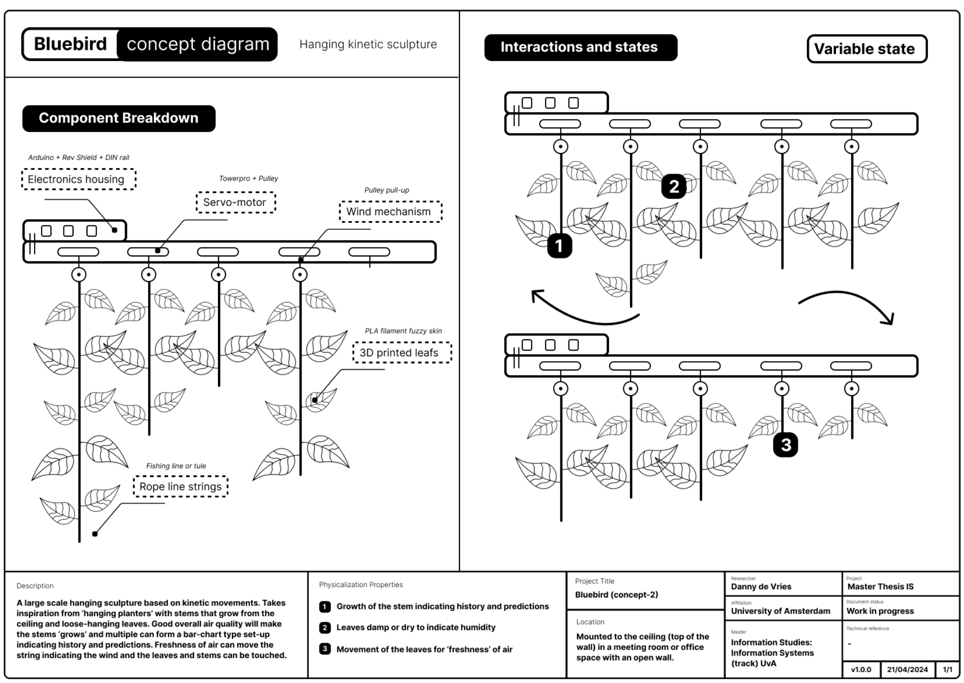


Figure 22: Design diagram of Concept-2

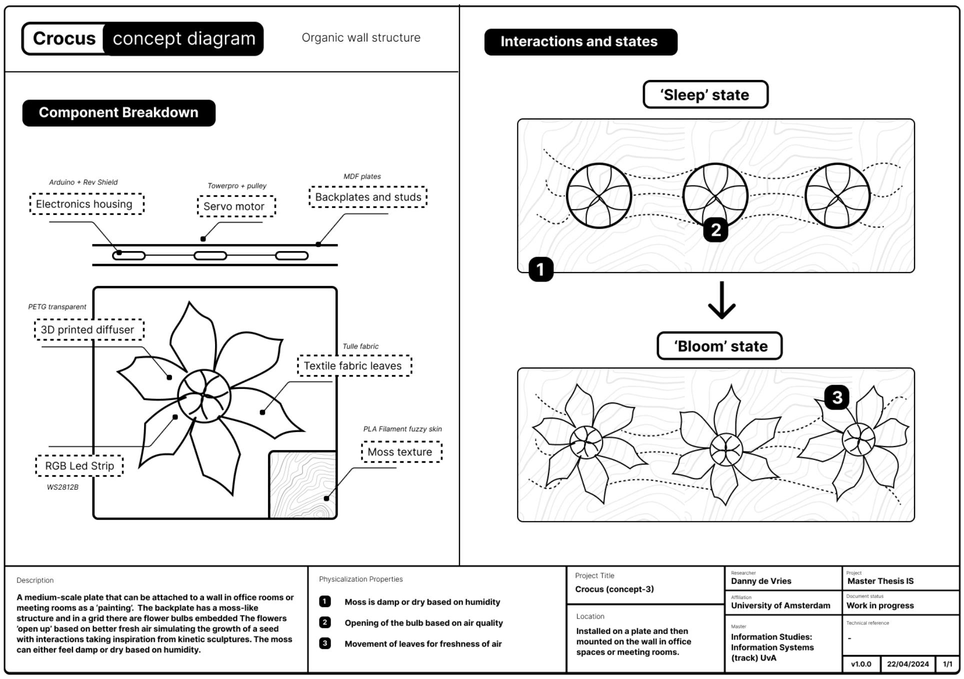


Figure 23: Design diagram of Concept-3

Appendix T ACADEMIC SAMPLE CASE STUDIES

In the ideation phase and development of concept models, seven academic publications were instrumental in informing and inspiring the design process. Table 1 provides an overview of these publications, presenting details such as the title, authors, publication year, and relevant venue.

Table 4: Overview of the 7 academic case studies used for the ideation phase and concept models.

Nr.	Sample	Author(s)	Year	Venue	Reference
1	Econundrum	Unknown	Unknown	non-academic	Econundrum
2	Caimform	Unknown	Unknown	non-academic	Caimform
3	Dataponics	Unknown	Unknown	non-academic	Dataponics
4	Garden of Eden	Unknown	Unknown	non-academic	Garden of Eden
5	Pudica	Unknown	Unknown	non-academic	Pudica
6	ComfortBox	Hamed S. Alavi et al.	2017	IFIP	ComfortBox
7	ComFeel	Ugo Sassi et al.	2020	ACM	ComFeel
8	WindowWall	Patrick Bader et al.	2020	ACM	WindowWall
9	Ambient Influence	Yvonne Rogers et al.	2010	ACM	Ambient Influence
10	Hilo-wear	Shailin Zong et al.	2020	CHI	Hilo-wear

Appendix U NON-ACADEMIC SAMPLE CASE STUDIES

In the ideation phase and development of concept models, an exploration of non-academic case studies were instrumental in informing and inspiring the design process. Table 2 presents an overview of the 15 non-academic case studies. Each entry in the table includes essential details such as the title, creator, publication year, and a brief description of the case study's venue.

Appendix V FABRICATION TECHNIQUES

Table 5: Overview of the 28 non-academic case studies used for the ideation phase and concept models.

Nr.	Sample	Creator	Year	Venue	Reference
1	Birdie Design	Birdie Design	2024	non-academic	www.bir.die
2	Fields of Informality	Zhestkov	2024	non-academic	www.artco.m
3	Tree of Ténéré	Studio Drift	2024	non-academic	www.studiodr
4	Kinetic Sculpture	ART+COM	2024	non-academic	www.artco.m
5	Electro Magnetic Field	Unknown	2024	non-academic	-
6	Microsurgical Robot	Unknown	2024	non-academic	-
7	Wind 3.0	Studio Roosegaarde	2024	non-academic	www.studior
8	Floralis Generica	Eduardo Catalano	2024	non-academic	-
9	Lucid Stead	Phillip K. Smith III	2024	non-academic	-
10	Flylight	Studio Drift	2024	non-academic	-
11	Spectra 2	FIELD	2024	non-academic	-
12	Meadow	Studio Drift	2024	non-academic	-
13	Wind Pavilion	Studio Roosegaarde	2024	non-academic	-
14	Pet Lamp	Álvaro Catalán	2024	non-academic	-
15	Living map	Unknown	Unknown	non-academic	Living map
16	Harassment plants	Unknown	Unknown	non-academic	Harassment plants
17	Popsicles of Pollution	Unknown	Unknown	non-academic	Popsicles of Pollution
18	Yellow Dust	Unknown	Unknown	non-academic	Yellow Dust
19	Touching air	Unknown	Unknown	non-academic	Touching air
20	Physical Weather Display	Unknown	Unknown	non-academic	Physical Weather Display
21	Inequalities Quipu	Unknown	Unknown	non-academic	Inequalities Quipu
22	Summer in the city	Unknown	Unknown	non-academic	Summer in the city
23	WeatherWindow	Unknown	Unknown	non-academic	WeatherWindow
24	Point cloud	Unknown	Unknown	non-academic	Point cloud
25	Tele-present water	Unknown	Unknown	non-academic	Tele-present water
26	Real-time Warning	Unknown	Unknown	non-academic	Real-time Warning
27	airFIELD	Unknown	Unknown	non-academic	airFIELD
28	Shanghai Spheres	Unknown	Unknown	non-academic	Shanghai Spheres

Table 6: Overview of the 4 academic and 6 non-academic sample case studies used as inspiration for fabrication of the prototype.

Nr.	Sample	Author(s)	Year	Venue	Reference
1	FibeRobo	Jack Forman et al.	2023	MIT Media Lab (TGM)	TGM
2	DefeXtiles	Jack Forman et al.	2020	MIT Media Lab (TGM)	TGM
3	Cilllia	Jifei Ou et al.	2016	MIT Media Lab (TGM)	TGM
4	UniMorph	Felix Heiberg et al.	2015	MIT Media Lab (TGM)	TGM
5	Geometric Floating Fabric	Billie Ruben	2020	non-academic	Printables
6	Print On Fabric	Damien Jorrand	2021	non-academic	Thangs
7	Nasa Fabric Mk3	John Bowler	2018	non-academic	Thingiverse
8	Servo Flower	Job Smolders	2018	non-academic	Pinshape
9	Multiuse Flexible Fabric	Posix	2024	non-academic	Printables
10	Leaf Decorative Holder	Trilobyte3D	2022	non-academic	Printables