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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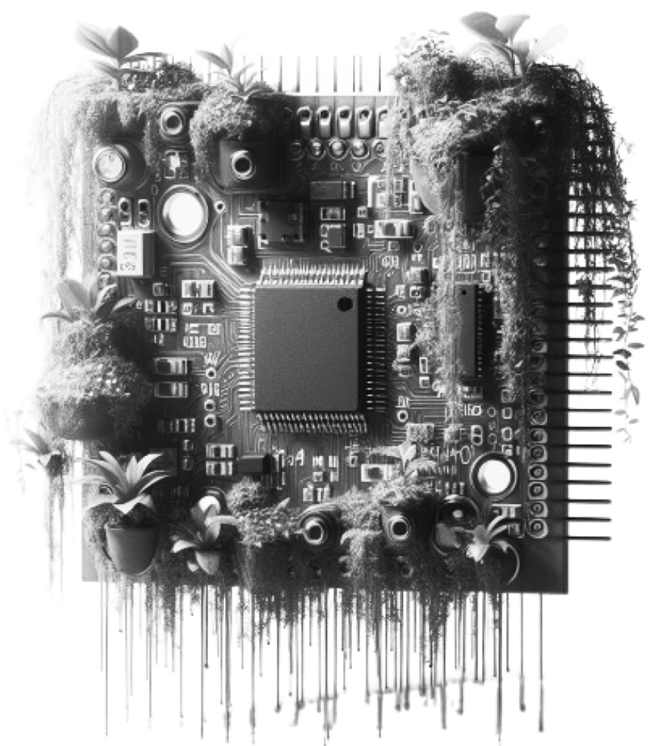

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ABSTRACT

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 'Bluebird', 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 5) 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 design solutions that display environmental data and computing installations communication data to building occupants for awareness. Particularly within the field of physically visualizing data to convey IAQ to building occupants in real-time.

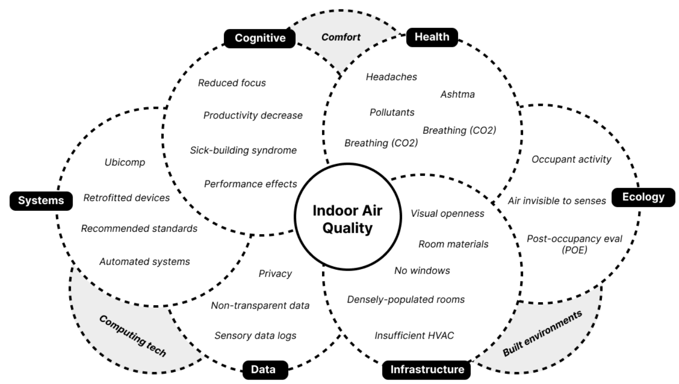

Figure 1: Complexity diagram providing an overview of the effects of IAQ and needs of occupants [2, 14, 28, 30, 45, 54]

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 indoor air quality be physically visualized to increase awareness among occupants facilitating their adoption of preventive measures against suboptimal 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 aware are occupants of their perception of indoor air quality and their understanding of its subjective properties?*
- SQ2: *How can environmental information related to indoor air quality be incorporated into a physical data-driven representation in the form of a design artefact?*
- SQ3: *How does the post-installation evaluation of a prototype design solution impact occupants' awareness and their willingness to adopt preventive measures?*

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 (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.

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

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 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 create awareness and nudge occupants to a desired behavior and rarely on large-scale architectural intervention that is the focus of this research. 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 I). Lab42 is an energy-neutral, flexible, and adaptable faculty building that facilitates collaborations among students, researchers, and businesses [6]. Since most of the space within the building are designated as informal learning spaces and another large part of the building is designed as meeting rooms (see Appendix H) occupants are most likely to experience the effects of poor indoor air quality within the meeting rooms due to the rather dense and crowded indoor environment. 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.

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

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 N).

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) similar to Customer Satisfaction (CSAT) surveys. 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.

[6]https://jupyter.org/
[7]https://pandas.pydata.org/
[8]https://seaborn.pydata.org/

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 G). 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

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 **??**, Appendix M). 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 creation of a prototype illustrates the technology to be and are often deployed to conduct lab experiments and case studies [26]. The overall goal of the physicalization 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.*

The goal of the prototype is to generate knowledge about the intervention and human behavior around it. This is in alignment with a pragmatist methodology in design research where methods are adapted and evolve through interactions with participants. 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 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

Figure 2: Impressions of the prototyping and ideations phase

[9] https://airteq.eu/producten/touch-aero/
[10] https://www.atal.nl/atu-ct-climatrend-binnenklimaat-datalogger
[11] http://dataphys.org/list/gallery/

[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 U). 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 V).

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 **??**) in order to choose one to develop in high fidelity (hi-fi) for the user studies and evaluation.

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 J).

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 learnability, memorability and usefulness using in-person evaluation sessions. To measure these properties of understanding and usability of the data physicalization we adopted and rewritten questions from the Technology Acceptance Model (TAM), Software Usability Measurement Inventory (SUMI) and System Usability Scale (SUS) to gather insight into perceived usefulness, attitude towards using, and system usability[11, 15]. These questions acted as a baseline and starting point but where revised and remixed to suit the specifics of evaluating data physicalizations within the context of this research (see Appendix Q).

3.5.1 Hypothesis elicitation. Based on the research question and creation of the prototype four hypotheses ("h" for "hypothesis") were formulated which also acted as evaluation criteria to evaluate upon in the evaluation session 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 (ease of learning)
- H2: **Engagement:** users will see the utility of the design and aesthetics of the physicalization and exhibit feedback on the quality of the design.
- H3: **Self-reflection:** users exposure to real-time IAQ data visualizations through the prototype will prompt users to reflect and behavioural or attitude change stimulation.
- H4: **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 recruited through internal communication of the studies via email and internal lab messaging tools. The participants were not involved in the development of the prototype and had no prior knowledge of the purpose of the prototype and its design of it. Participants were not (financially) incentivized to take part in the studies. 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. 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 Q). 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. Some questions were purposefully vague to explore how the building occupants understand and use the prototype. Also in these cases the purpose of the prototype was not communicated to participants before-hand to gather first impressions.

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

[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

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 R). 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 S). 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.

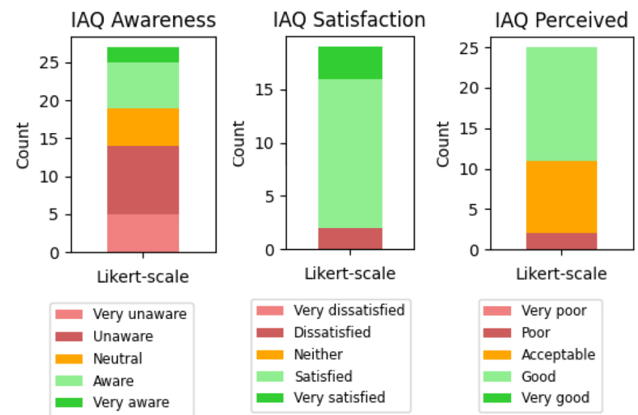

Figure 3: Likert-scales of IAQ awareness, perception and satisfaction of the questionnaire survey with occupant count

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 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.

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

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. The process of breathing accumulates CO2 and the air quality within a space is heavily influenced by the 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.

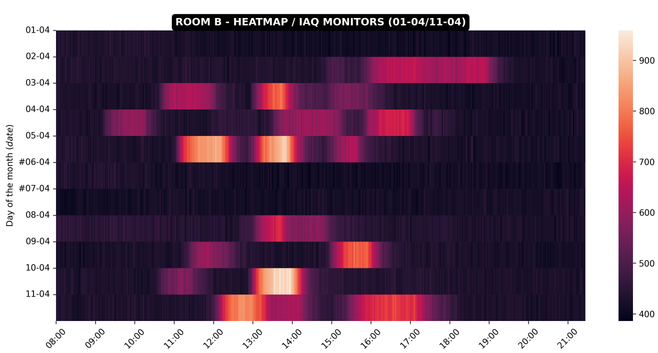

Figure 4: Heatmap of ten days of data logs from Room B showing the peaks of CO2 concentrations monitored

4.2.1 Single meeting CO2 development. A sample of CO2 concentrations in a single meeting is shown in (see Figure 5). 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.

4.2.2 Regular day CO2 development. The visualization (see Figure 5) 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 5) 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 fostering the relationship with nature. It is meant to be hung from the ceiling in small to medium rooms and changes based on real-time air quality monitor data engaging the occupants within the room into considering the level of air quality. 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]. A unique characteristic of the prototype as opposed to existing (commercially available) solutions is that it shows predictions and history, so not only feedback on the current situation when the situation of high CO2 concentrations already occurred.

4.3.2 Experimental set-up. The prototype was installed *in situ* within one of the monitored meeting rooms inside of the building. We derived four relevant dimensions to describe the prototope based on the literature; *properties, environment, interaction, representation* [4, 21, 43].

- **Properties**: The technology-assisted physicalization uses explicit visual variables such as size, position, timing and movement. The better the air quality the more the string of the plant can 'grow' acting as a metaphor for plant 'growth' where occupants visually see the strings becoming larger (height). Making the movement of the physicalization dynamic and changed based on temporal frequency of CO2 concentrations. If fresh air comes in we indicate this through the movement of the leaves as a metaphor for wind gusts to change the visual arrangement (movement). Touching the leaves of the physicalization is an implicit haptic property.
- **Environment**: The design uses associative design metaphors through visual hints of shapes and movement and uses organic shapes and forms resembling shapes found in nature (shape and form). It is a medium to large scale (50 - 150cm) physicaliation. The physicalization is semi-public placed within the context of an open building.
- **Interaction**: The physicalization is a tool for communicating environmental data assists with understanding information and encourages reflection and self-reflection. The design includes indirect interaction where the physicalization changes based on occupant activity.
- **Representation**: The dataset is dynamic from a real-time stream of environmental data using building sensors using categorical data as output calculating differences in CO2 concentration values.

4.3.3 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 paracord rope simulating the growth of the hanging planter so that the string can be moved up and down. All electronics are integrated at the back of a wooden board, enabling the device to act as a stand-alone device making it movable and modular to be installed in other spaces.

4.3.4 Crafting technologies and materials. The strings, leaves, and housings of the electronics and mechanical hardware are digitally-fabricated 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.

[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/

4.3.5 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 L). 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]. Some custom library functions are written in to calculate the movements of the string. The current (C_{current}) and previous C_{previous} CO2 concentrations are stored on which a difference number is calculated. The difference number is mapped to a movement time t_{movement} in milliseconds using a multiplication factor. Based on a negative or positive integer the servo motors spin either clockwise (growing) or counterclockwise (shrinking) the ropes.

4.4 Evaluation

The prototype-led evaluation sessions (see 3.2) were held to assess the quality and impact of the data physicalisation with a focus on how users perceive the data embedded in the physical representation, gain insight into it's effectiveness and suggestions for design recommendation and improvements.

4.4.1 WIP (NOT FINISHED). Lorem Ipsum is simply dummy text of the printing and typesetting industry. Lorem Ipsum has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged. It was popularised in the 1960s with the release of Letraset sheets containing Lorem Ipsum passages, and more recently with desktop publishing software like Aldus PageMaker including versions of Lorem Ipsum.

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[21] https://www.arduino.cc/reference/en/
[22] https://lora-alliance.org/about-lorawan/

Figure 5: Installed photograph of the prototype in the room during an evaluation session with a participant

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5 DISCUSSION

Analyzing the grounded-theory research design and chosen methodologies of this study, along with interpreting the qualitative and quantitative findings reveals several comparative findings, study limitations and possibilities for future research.

5.1 Findings in context

Comparing the findings of the existing literature (see Section 2) with the results of the study of this paper (see Section 4), general findings were supported.

5.1.1 Occupant awareness and IAQ monitor. Occupant awareness about IAQ is generally low (SQ1) based on its inherent properties of not being easily detected by human sensory reception and the perception of the quality of indoor air by occupants is judged mainly by visible attributes within the indoor environment that in most cases don't influence the air quality in a positive way [45] [14]. Building activity, occupancy and crowdedness of a space largely have a negative impact on CO2 concentrations (SQ2) which is the main factor of suboptimal air quality within indoor environments. [19] [17] specifically within smaller spaces such as offices and meeting rooms [57].

5.1.2 Prototype development and evaluation. Due to the explorative nature of the research and the novelty of the data physicalization prototype (SQ3), it's difficult to compare these results directly and quantitatively to existing literature. However, the evaluation of the prototype uses a similar approach to other existing data physicalization studies [3, 24]. The evaluation sessions show an increase in understanding and self-reflection of data insights but no significant effect or success rate is observed if the data physicalization helps occupants take preventive action.

5.1.3 Key differences from comparitive studies. A key difference however is the human-centered design approach where feedback from occupants is incorporated throughout the iterative research process. The findings of one methodology informed decisions on how to further approach the study (see Section 3). Additionally, it should be noted that these comparative state-of-the-art studies also heavily vary in their context (e.g. outdoor environments, non-university buildings) and lab setting (e.g. households, classrooms) which differ from the Lab42 building. The additional step undertaken in this study was the creation of the prototype which goes beyond what has been observed in previous related studies.

5.2 Limitations

The design and validation process showed several strengths but also had some limitations that should be noted. The main limitations encountered during this study were the scalability and reliability of the prototype, the generalizability of findings to other buildings, and the adoption of standardized questionnaires.

5.2.1 Evaluation validity. Grounded theory is a well-established and widely recognized research method. However during the research more care and effort should have been taken for investigator and theory triangolution. Some concepts in the ideation phase possibly did not emerge, as only the main researcher was involved in the prototyping phase. During the evaluation sessions no other four-eyed principles were used to mitigate any researcher (confirmation) and interviewee bias leaving the interpretative nature of qualitative research. The evaluation sessions were done with a rather small sample size since interviews reached saturation but the methodology could have benefitted from a larger sample size for better generalizability and a more diverse demographic but mainly a more diverse interview setting (e.g. different sized meeting rooms, personal office spaces) to test the usability within different contexts. The homogenous setting the prototype was evaluated in may have influenced the results and limits the understanding of its effectiveness for a more diverse group. The same group of participants was used for both the interviews and the user study, which may have influenced their evaluation of the product during the user study. The initial interview responses could have biased their perceptions when assessing the product's effectiveness.

5.2.2 Prototype scalability. The prototype used for user studies is a proof of concept and should be further optimized. 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 and acknowledge that there is no universally perfect form of displaying air quality data that satisfies all users. 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). The current research setup cannot discover long-term intervention strategies of the prototype cause it requires testing over a longer period. During the prototype testing scenarios of high CO2 concentrations were simulated but the accuracy of the findings depend on actual real-life scenarios of which these situations occur. Together with the first limitation, this is the reason why only positive indications of the prototype are found in this study, and no hard conclusions can be drawn on it's effectiveness.

5.2.3 Building 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 causing a high attrition rate and may not be representative of a larger population. The convenience sampling approach used for participant recruitment may introduce sampling bias, as it primarily targets occupants present in specific areas of the building.It is not clear if the results can be externally validated and generalized from sample size to larger population. The specific context of Lab42 may limit generalizability to other buildings or environments with different characteristics.

5.2.4 Standardized questions reliability. This study uses similar approaches to the other studies in terms of utilizing the same dimensions and metrics (e.g. HCI evaluation, POE evaluation, standardized questionnaire questions) wherever possible but these methods have been slightly adopted and tweaked for this specific research influencing the reproducibility and validity of the results and gathering standardized quantitative calculations (Cron Alpha score e.g.).

5.2.5 Data collection. Care was taken to ensuring consistency in data collection using standardized high-quality sensors and well-defined procedures for data collection ensured reliable and consistent data it needs to be noted that he monitoring within the meeting rooms mainly focussed on envirnomental properties such as CO2 concentrations. No explicit data was gathered about how many occupants where in each meeting etc. The data collection phase could benefit from more context to intepret occupant behaviour and explain CO2 concentration patterns in more details as well as the effects of the mechanical ventilation already existing in the building.

5.3 Future work

Future research should focus on improving the design and communicative properties of the prototype and a more structured lab environment to gather more quantifiable results on the effectiveness of the prototype and helping occupants take preventive action long-term. E.g. installing window sensors to measure how often occupants in meetings open the windows. The absence of objective outcome measures limits the validity of conclusions regarding the prototype's effectiveness. Incorporating robust validity checks would enhance the credibility of the evaluation findings.

The current focus of the prototype is in terms of awareness to occupants and wellbeing purposes and not as a behavior-change intervention. Further research with a larger and more diverse sample is needed to establish its applicability. The evaluation of the prototype focusses on understanding and first impressions provide a framework for assessing prototype efficacy, the evaluation session lack validity measures and control measures for concrete effectiveness measurements. Broader behavioral data, such as how the intervention influenced participants' actions and behavior in daily life, need to be addressed in future deployment studies.

Extending the duration of product usage in future studies could yield more accurate results. We envision the prototype to communicate more sensory properties. We envision fabric that holds water to communicate humidity etc. made of organic materials etc. The prototype could have more material-driven feedback to further engage in more embodied experiences.

Without replication in diverse environments, the extent to which findings can be generalized to broader populations or settings is uncertain. Replicating the study across multiple buildings with diverse occupants would strengthen the generalizability of the findings. The unique characteristics of Lab42, such as its architecture and occupant demographics, may not be representative of other indoor environments.

6 CONCLUSION

The limited research on occupants' subjective comfort needs and the potential of visualizing IAQ data for building occupants is addressed in this study. Using a mixed-methods approach, it examines occupants' awareness of indoor air quality, correlating this with air quality monitoring data, and explores how physically communicating these properties can aid in increasing data insights and serve as an intervention strategy. The findings indicate that occupants are generally unaware of indoor air quality, often judging it based on visual aspects like open spaces and planters. Monitoring CO2 levels in meeting rooms shows that concentrations frequently reach sub-optimal thresholds, posing health and cognitive risks. The results of the developed prototype and evaluation of the data physicalization prototype suggest a positive attitude toward interpreting IAQ data and taking preventive actions, although these are preliminary indications without statistically significant results.

The limitations around the generalizability of the specific context of the case study university building and the sample size of the evaluation sessions should be considered when interpreting the conclusions and applying the findings to other contexts. Future research should aim to verify these findings in more diverse settings and further develop the design and aesthetics of the prototype to include even more environmental properties for multi-sensory interaction assuming it increases the effectiveness of the data physicalization. It also lays the groundwork for further research within the niche of data physicalization, addressing the research gap in understanding occupants' behavior to take preventive actions based on their indoor environment. Ultimately, this study contributes to the field of Human-Building Interaction by integrating computing technologies into built environments, aiding building staff and (responsive) architecture in making decisions about structuring spaces to engage with their occupants and improve their overall comfort.

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Appendix A ACKNOWLEDGEMENTS

My sincere gratitude to all the participants who generously contributed to this research by dedicating their valuable time to respond to the questionnaires voluntarily, as well as the participants who willingly tested and interacted with prototypes created for this research for their feedback and evaluation through interviews. Additionally, I thank everyone who supported me in the data gathering and prototyping phase by providing hardware, testing, and debugging code.

Special appreciation goes to Shruti Rao Ph.D. Candidate (University of Amsterdam) for her constructive feedback and suggestions, which further expanded this research, and internal supervisor Dr. Hamed S. Alavi (University of Amsterdam), for his invaluable guidance and thought-provoking questions throughout the project. Also, my sincere appreciation to all the reviewers of this research, particularly drafts of this paper, for their insightful comments and contributions.

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. Participants were not (financially) incentivized to take part in the studies. 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 PROTOTYPE BUDGET AND COSTS

Some of the hardware components and materials were bought specifically for the creation of the prototype. These costs were declared to the Digital Interactions Lab (DIL) and deducted from the lab budget. All other components were already in possession of the researcher. The author(s) has no affiliation with any of the hardware companies and organizations mentioned in this paper and received no other financial support for the creation of the prototype.

Appendix F 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' 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: https://github.com/viszlab/

[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

Appendix G FLOORPLAN AND LAB SET-UP

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

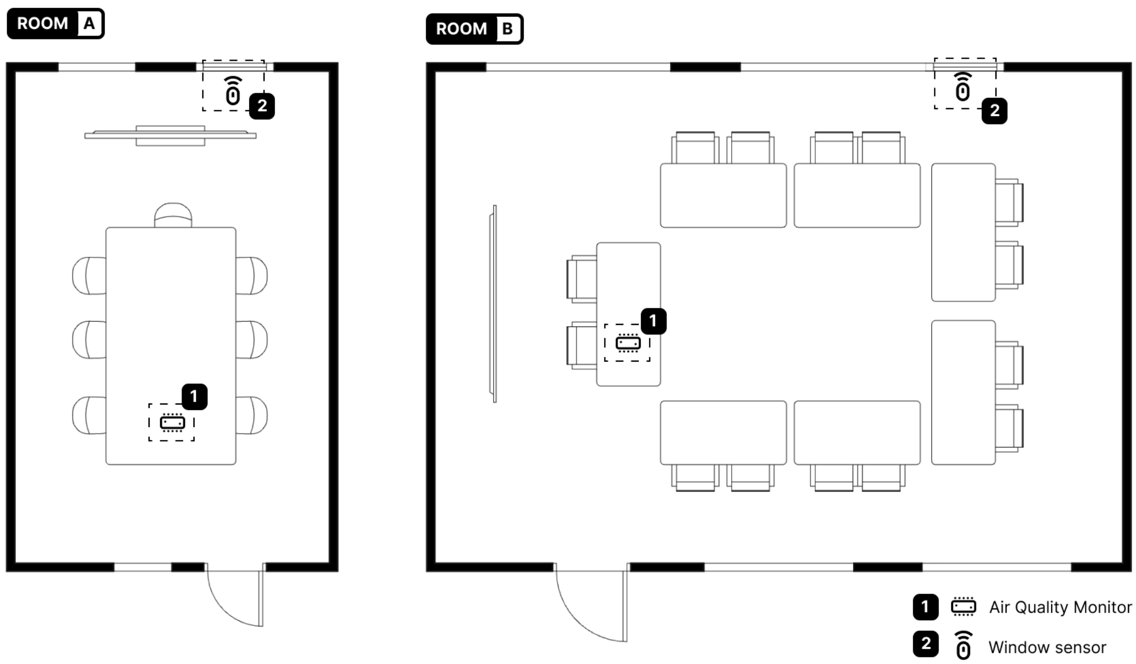


Figure 6: Floorplan of Room A and B with the position of the monitor devices installed to manufacturer specifications

Appendix H MEETING ROOM IMPRESSIONS

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

Figure 7: The 'smaller'($m2$) space labeled Room A

Figure 8: The 'larger' ($m2$) space labeled Room B

Appendix I BUILDING IMPRESSIONS

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.

(a) Single meeting CO2 concentrations in Room A **(b) Single meeting CO2 concentrations in Room B**

Figure 9: IAQ monitoring CO2 concentrations of a single sample meeting based on the start and end time of the meeting

(a) Single meeting CO2 concentrations in Room A **(b) Single meeting CO2 concentrations in Room B**

Figure 10: IAQ monitoring CO2 concentrations of a single sample meeting based on the start and end time of the meeting

(a) Single meeting CO2 concentrations in Room A **(b) Single meeting CO2 concentrations in Room B**

Figure 11: IAQ monitoring CO2 concentrations of a single sample meeting based on the start and end time of the meeting

Appendix J PROTOTYPE IMPRESSIONS

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.

(a) Single meeting CO_2 concentrations in Room A

(b) Single meeting CO_2 concentrations in Room B

Figure 12: IAQ monitoring CO_2 concentrations of a single sample meeting based on the start and end time of the meeting

(a) Single meeting CO_2 concentrations in Room A

(b) Single meeting CO_2 concentrations in Room B

Figure 13: IAQ monitoring CO_2 concentrations of a single sample meeting based on the start and end time of the meeting

(a) Single meeting CO_2 concentrations in Room A

(b) Single meeting CO_2 concentrations in Room B

Figure 14: IAQ monitoring CO_2 concentrations of a single sample meeting based on the start and end time of the meeting

Appendix K IOT ARCHITECTURE OF THE PROTOTYPE

System diagram which shows the IoT architecture of the prototype.

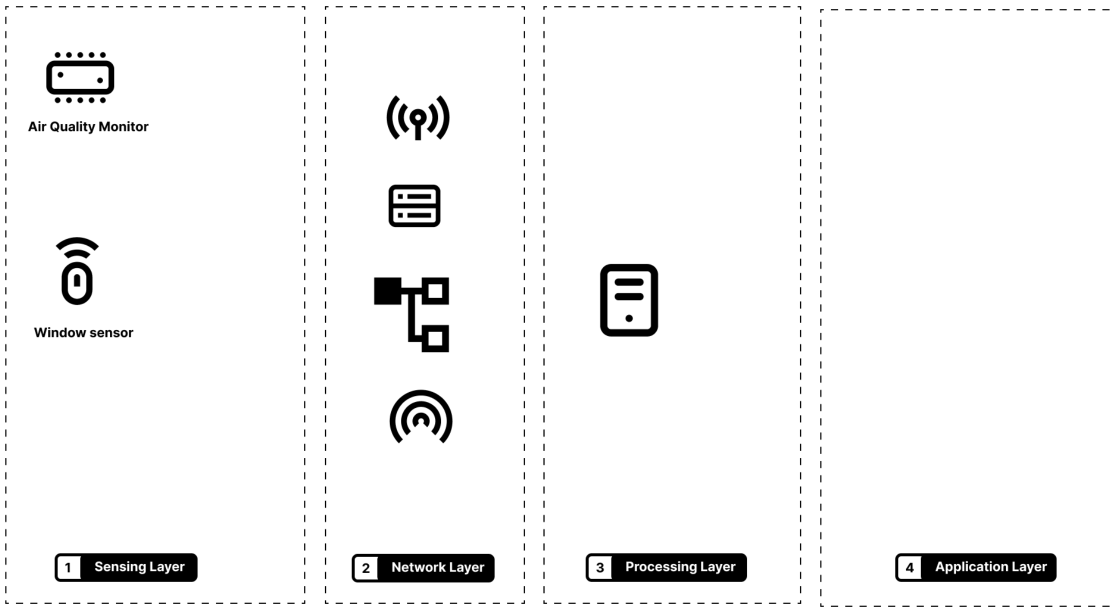


Figure 15: System diagram that shows the technical set-up of the prototype

Appendix L EXISTING BUILDING API SAMPLE DATA

Overview of the current building API with outputs.

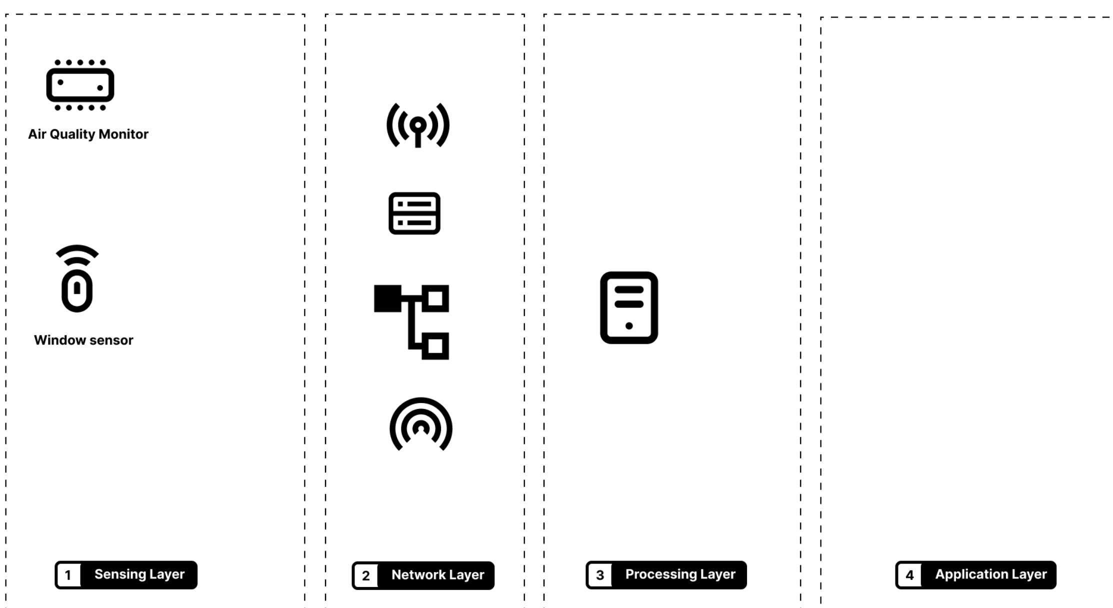


Figure 16: System diagram that shows the technical set-up of the prototype

Appendix M 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 1: 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 2: Sample data log of the Atal ATU-CT ClimaTrend installed in the 'large' Room B

Appendix N 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*

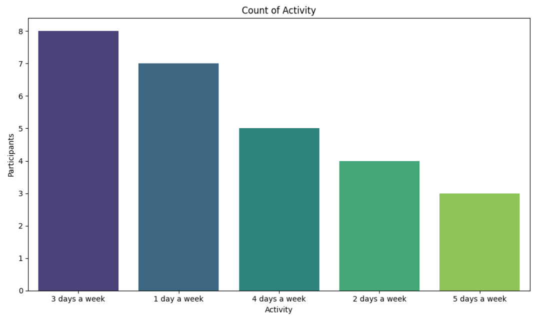
- None
- Headaches
- Trouble breathing
- Feeling nauseating
- Other

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*

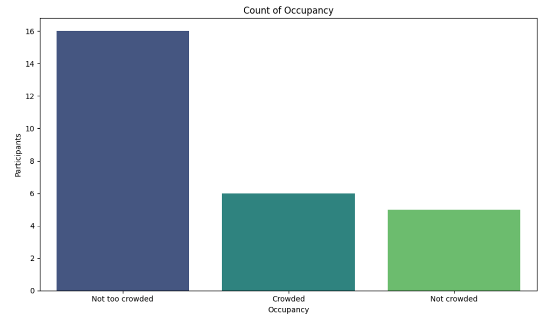
- None
- Trouble with focus
- Decreased productivity
- Tiredness
- Other

Appendix O SURVEY DATA

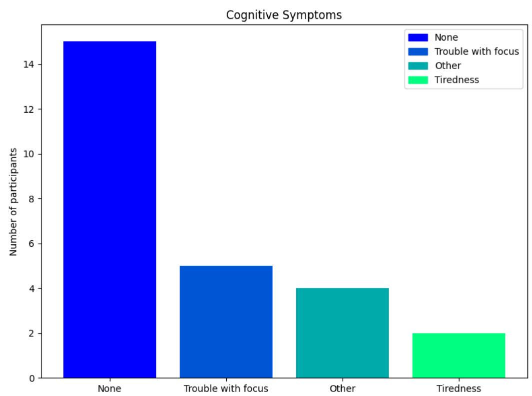
Plots of the results of the survey data exported from Qualtrics.



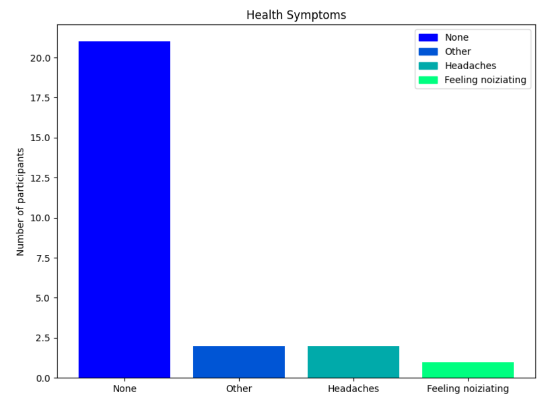
(a) Average use of the building for various activities



(b) Description of occupancy crowdedness

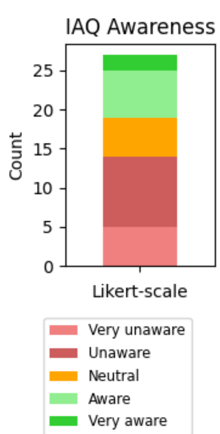


(c) Cognitive symptons based on the air quality

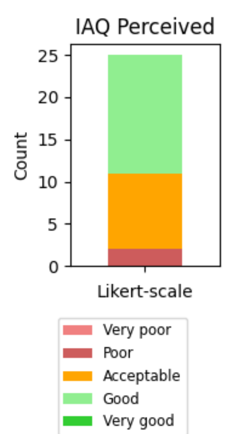


(d) Health symptons based on the air quality

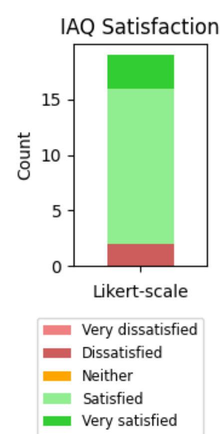
Figure 17: Bar charts of the survey questions about activity, occupancy, health and cognitive symptons



(a) Awaneress



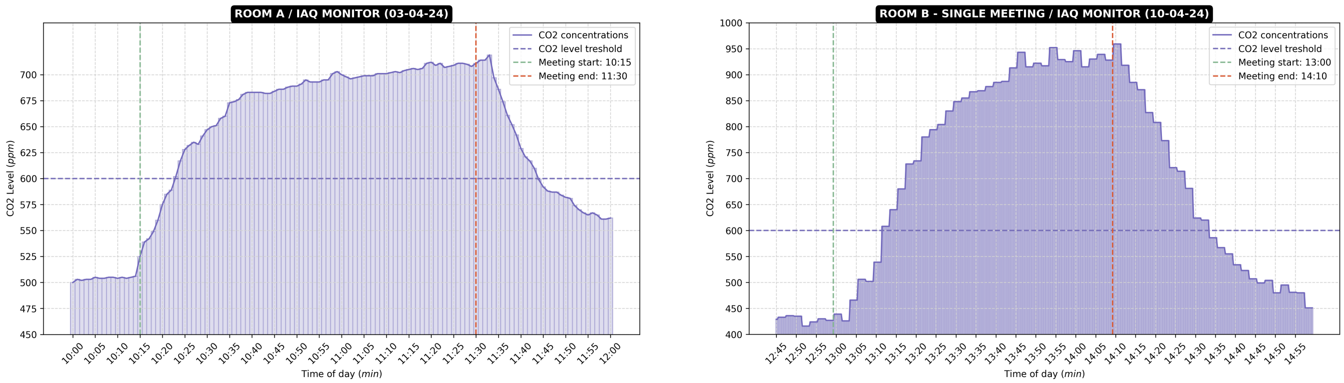
(b) Perceived



(c) Satisfaction

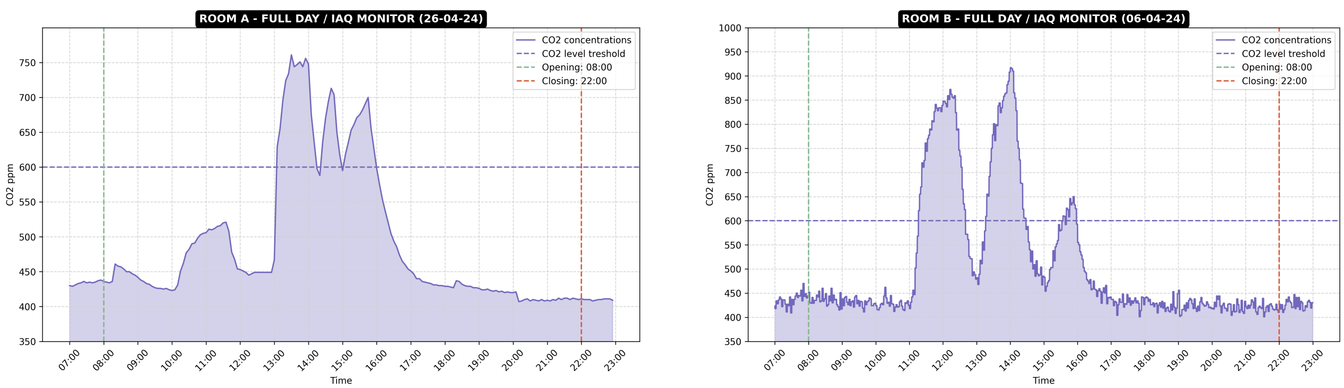
Figure 18: Stacked bar charts of the Likert-scales on IAQ awareness, perceived and satisfaction

Appendix P MONITOR DATA



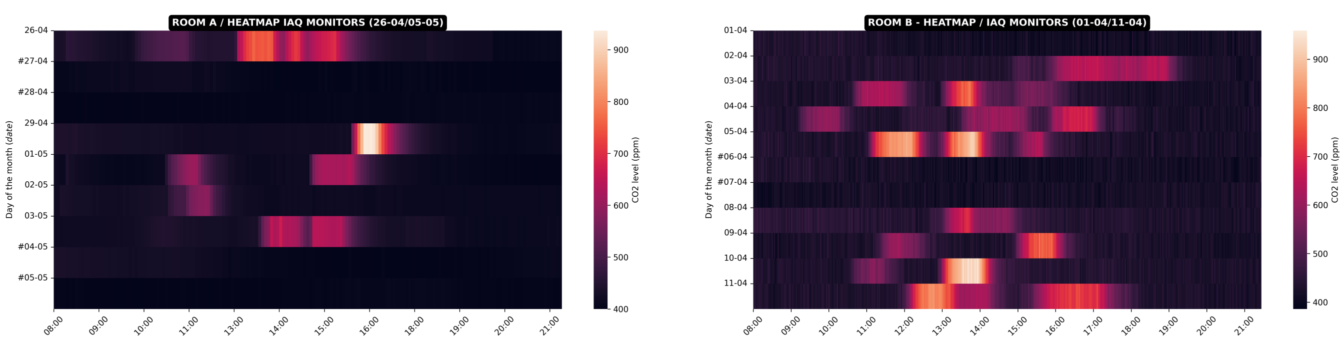
(a) Single meeting CO2 concentrations in Room A **(b) Single meeting CO2 concentrations in Room B**

Figure 19: 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 20: 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 21: IAQ monitoring heatmap CO2 concentrations of the sample ten days based on the opening hours of the building

Appendix Q EVALUATION INTERVIEWS

The evaluation session was conducted in English. The questions and structure below served as a guideline for the interviews. It was a semi-structured interview so the questions acted as guiding questions only. The first part of the evaluation session was done sitting at the meeting room table.

Introduction:

First of all, thank you for participating in this evaluation study researching indoor air quality and testing the proof-of-concept prototype Bluebird. This evaluation study consists of three parts, 1) a semi-structured interview with questions about your activity within this building and notion of IAQ 2) a usability test of the functioning and perception of the prototype and 3) a score questionnaire rating the prototype on several properties. As a participant you cannot do anything wrong, this is a prototype so only it can malfunction. During the testing I will ask you to think out loud and will ocassionaly ask follow-up questions. Pilot tests of this evaluation session indicated that it will take ~50 minutes.

Informed Consent:

Your participation will be fully anonymized. If you agree, I will record this meeting for archival purposes and transcription. If you feel uncomfortable at any point during this evaluation session, please feel free to stop it at any point. If you don't want to answer any specific questions feel free to state that you would like to skip and I will move on to the next question.

Question-set 1: *Demographics and roles*
Introduction: First I'm going to ask some questions about your demographics and use of this building.

Description	**Questions (open-ended)**
Demographics for sample size	**Q1:** What is your age? **Q2:** What gender do you identify with? **Q3:** What is your nationality? **Q4:** What is your level of education?
Role of the occupant	**Q5:** What do you do in daily life for work? **Q6:** How would you describe your role within this building? **Q7:** Where are you usually stationary located in the building?

Question-set 2: *Activity and frequency*
Introduction: Now on to some questions about your activity within this building and how you use the meeting rooms.

Description	**Questions (open-ended)**
Frequency of activity	**Q8:** How often do you use this building for various activities? **Q9:** For what types of activities do you usually use the building for?
Frequency of meetings	**Q10:** On average how many meetings do you have per week? **Q11:** On average how long is a typical meeting you attend? **Q12:** What locations do you typically use for your meetings?

Question-set 3: *Notion of Indoor Air Quality (IAQ)*
Introduction: Lastly some question about your notion of indoor air quality as a baseline.

Description	**Questions (open-ended)**
IAQ awareness	**Q11:** How aware are you of the current IAQ in this space? **Q12:** How do you perceive the IAQ in this space?
Cognitive and health	**Q13:** Have you ever experienced cognitive symptons related to IAQ in a meeting room? **Q14:** Have you ever experienced health symptons related to IAQ in a meeting room?

Appendix R USABILITY TESTS

For the usability tests we shifted attention towards the prototype that was installed in the meeting room. In all sessions the researcher and occupants stood up and walked towards the prototype. The occupants were allowed to touch the prototype and during the questions the researched changed the state of the prototype so the live movement could be observed.

Introduction:

We will move on to testing the prototype. Please imagine you are an occupant having a meeting in the space (meeting room) we are currently in. As you might have noticed on the wall hang from the ceiling, a prototype of a physical artefact is hung up.

Question-set 1: *Understanding of the prototype (learnability)*
Introduction: To gather some first impressions I would like to get some description of the prototype based on your view of it.

Description	**Questions (open-ended)**
Description of prototype	**Q1:** Could you describe in your own words what the physical artefact is?
Look and feel	**Q2:** What do you think of the overall design of the physical artefact?
Use of materials	**Q3:** What do you think of the materials the physical artefact is made of?
Communicative properties	**Q4:** What properties do you think the data physicalization communicates?

Question-set 2: *Self-reflection of data insight (memorability)*
Introduction: I want to gain insight into how likely you are to take preventitive action based on data insights.

Description	**Questions (open-ended)**
Behavourial change	**Q5:** How and to what extent do you think your awareness of IAQ changes? **Q6:** How willingly are you to take preventitive action based on the data insights the artefact provides?

Question-set 3: *Design improvements and further development*
Introduction: After interacting with the prototype for a bit. This usability test concludes with suggestions for design improvements.

Description	**Questions (open-ended)**
Good characteristics	**Q7:** What do you think is the best aspect of this data physicalization, and why?
Design improvements	**Q8:** What do you think needs most improvement of the design, and why?
Further development	**Q9:** Is there anything that you would wish to be considered further development of the prototype?

Appendix S EFFECTIVENESS SCORES

That concluded the usability test, thank you for thinking out loud and suggesting improvements. The last part is an online score rating statements and hypothesis about the prototype. The occupant and researcher sit down on the table again and the occupant is handed an iPad to fill-in an online questionnaire on Qualtrics with scores.

Effectiveness scores *Rating statements and hypothesis*
Introduction: Please rate the following statements based on the five-point scale (likert)

Description	**Statements (Likert-scale 5 points 1: Strongly disagree 5: Strongly agree)**
Attitute towards using	**S1:** I enjoyed viewing the data physicalization and interacting with the prototype
Perceived Ease of use	**S2:** I thought the data physicalization was easy to use and interpret
Learnability of data	**S3:** I would imagine that most people would learn to use the data physicalization very quickly
Perceived Usefulness	**S4:** I derived insights into state of the indoor air quality based on the data physicalization
Behavioural Intention	**S5:** I likely will change my behaviour and take preventive measures based on the data insights

Final remarks:

Do you have any other final remarks you want to share about the prototype? If not, this marks the end of this evaluation session. Thank you so much for your valuable time, insights and feedback. If you want any more information or the published results of this research please contact me.

Appendix T CONCEPT DIAGRAMS

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

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.

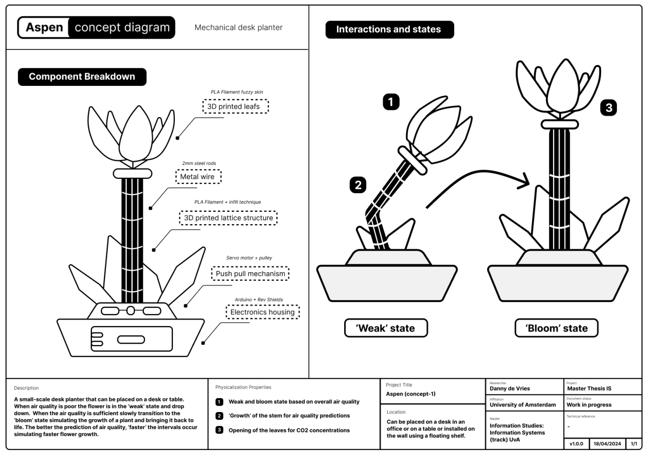


Figure 22: Design diagram of Concept-2

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.

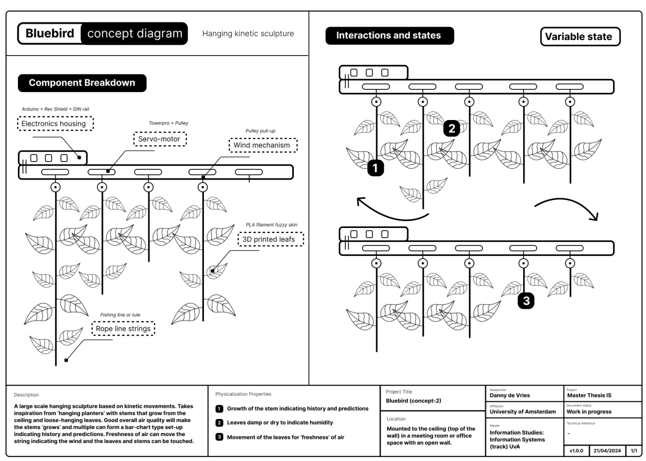


Figure 23: Design diagram of Concept-2

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.

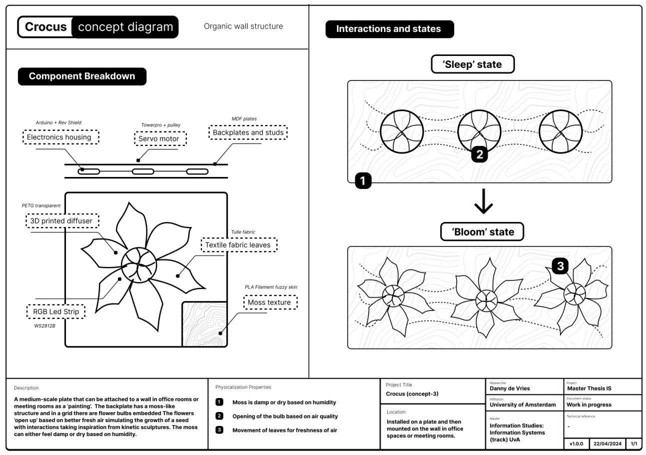


Figure 24: Design diagram of Concept-3

Appendix U 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 3: 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 V 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 W FABRICATION TECHNIQUES

Table 4: 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 5: 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