# A BREATH OF FRESH AIR: TOWARDS OPTIMAL INDOOR AIR QUALITY

## INVESTIGATING INTERVENTION STRATEGIES FOR ENHANCING OCCUPANTS AWARENESS, COMFORT AND HEALTH

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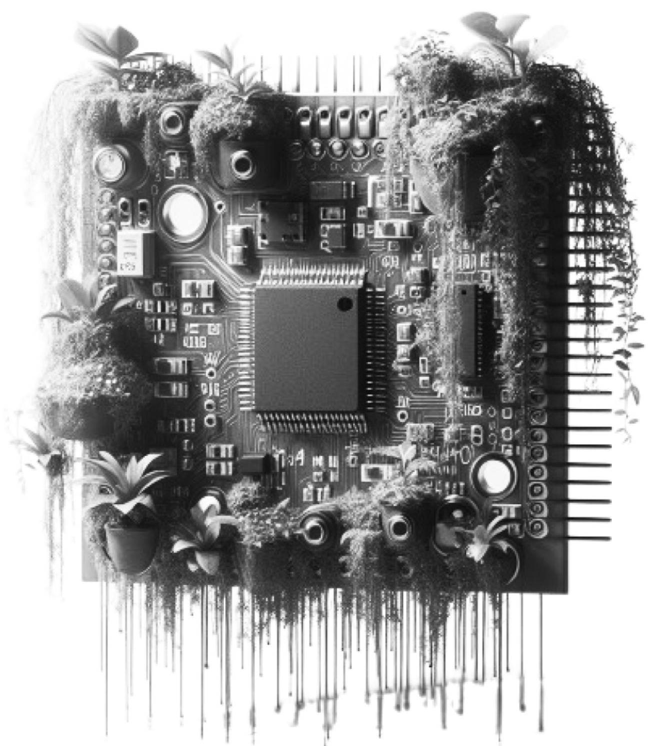

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## ABSTRACT

Suboptimal indoor air quality (IAQ) poses health risks and affects the cognitive performance of occupants within indoor environments. Despite growing awareness, there is a significant gap in communicating IAQ data to occupants. This study addresses this gap by developing 'Bluebird,' an interactive data physicalization that visualizes real-time air quality data to enhance occupant awareness. Using a user-centered mixed-methods approach, this study employs post-occupancy evaluation (POE) methods within the Lab42 case study building to elicit occupants' understanding of IAQ ($f$=29) and utilizing air quality monitors to collect and measure $CO_2$ concentrations within meeting rooms (30-day period). The insights guide the development of the data physicalization which was subsequently evaluated and usability-tested with occupants ($n$=5). The results reveal a need for more awareness among users regarding indoor air quality highlighting that $CO_2$ concentrations regularly exceed the optimal threshold within meeting rooms. Evaluations of the data physicalization indicate that real-time environmental data can effectively increase occupants' awareness and suggest it can support them in taking preventive action.



## KEYWORDS

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


## 1 INTRODUCTION

Globally, people are estimated to spend approximately 90% of their time indoors [29, 44] and breathe 11.000 liters of air per day [13]. Poor indoor air quality (IAQ) conditions affect building occupants' experiences of comfort, and insufficient ventilation in indoor environments is proven to play a significant role in occupants' well-being, health, and cognitive functions [27, 53].

The overall indoor environmental quality (IEQ) influences the perceived comfort of occupants consisting of several key metrics (e.g., mechanical ventilation, temperature regulation, natural lighting) to create a combined IEQ index for a specific indoor space [30]. Among these metrics, indoor air quality stands out as a crucial factor deserving special attention due to its invisibility to occupants [46]; 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 [45], which contributes to occupants' perceived lack of control. These systems are typically automated [37] and cannot be directly regulated or controlled by occupants themselves [26].

This research aims to understand occupants' needs through in-the-wild [41] studies gaining insight into occupants' awareness, collecting indoor air quality data in designated spaces, prototyping a data physicalization device to visualize indoor air quality, and evaluating its effectiveness as a data probing tool [57]. With the overarching objective of enhancing occupants' comfort levels and facilitating their adoption of preventive measures against poor indoor air quality [56]. This research contributes to the overarching interdisciplinary field of Human-Building Interaction (HBI), which explores novel forms of technology and interactions that shape human experiences in built environments [1]. This interplay and complexity between occupants' effects on comfort, built environments, and computing technologies are visualized in a diagram shown in Figure 1. While research on defining comfort within indoor buildings [2], gathering and analyzing sensory air quality data [13] and the effects of poor air quality are prevalent [29], there remains a research gap in understanding occupants' awareness 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.

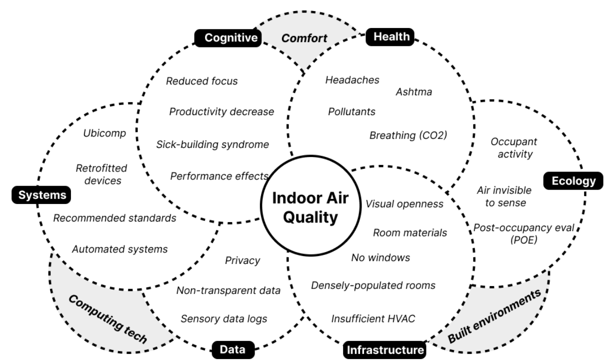


**Figure 1: Complexity diagram providing an overview of the effects of IAQ and needs of occupants [2, 13, 27, 29, 44, 53]**

### 1.1 Research questions

In order to research effective ways of communicating IAQ data, 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 central research question, the following supporting sub-questions guide this research and serve as objectives to delineate the necessary knowledge:

- SQ1: *How aware are occupants of indoor air quality, and how do they understand and perceive its subjective properties?*
- SQ2: *How can environmental information related to indoor air quality be incorporated into a physical data-driven representation?*
- SQ3: *How do initial experiences of a prototype design solution influence occupants' awareness of indoor air quality and their willingness to adopt preventive measures?*

## 2 RELATED WORK

Given the focus on Human-Computer Interaction (HCI) within Built Environments (BE), this research draws from Human-Building Interaction (HBI) (see Section 2.1) and narrows its scope to Comfort within Buildings (see Section 2.2) and indoor air quality (IAQ) (see Section 2.3). Additionally, it examines previous approaches to mapping and encoding sensory data in the field of Data Physicalization (DataPhys) (see Section 2.4).

### 2.1 Human-Building Interaction

Buildings increasingly incorporate new forms of digital interaction [33, 38], which means new inherent connections between 'people', 'built environments' and 'computing' research in an area called Human-Building Interaction (HBI) [1, 51]. This research area is dedicated to exploring the design of built environments that may incorporate computing to varying degrees [48]. A logical extension where indoor spaces are increasingly retrofitted with sensing devices [38]. These sensing devices usually come in the form of ubiquitous computing (ubicomp) [9] devices that seamlessly blend into the environment, essentially making the computing devices 'disappear' [55].

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. [52]. 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 [43]. Additionally, architects and interior designers often integrate computing devices into indoor spaces overlooking the human experience [24, 28], leaving occupants with a perceived lack of control over their indoor comfort.

### 2.2 Comfort within buildings

Indoor occupant comfort is interaction with the environment and manifests in four respective dimensions: thermal, respiratory, visual, and acoustic [2]. Indoor Environmental Quality (IEQ) [30] indexes serve as metrics for assessing the aforementioned properties of comfort with Post-Occupancy Evaluation (POE) [17] and Perceived Environmental Qualities (PEQ) [46] methods 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] and 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. [46]. 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' [31] 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 is reportedly associated with health-related problems such as headaches, throat irritation, and asthma [29] as well as a decrease in cognitive functions such as tiredness, effects on performance and productivity and a lack of focus [53] [16]. A phenomenon referred to as the Sick Building Syndrome (SBS) [19, 36]. Many of these symptoms are primarily associated with respiratory comfort and are closely tied to indoor air quality (IAQ) concerns [27]. Effective ventilation strategies have significantly alleviated SBS symptoms [19].

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 [35]. 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 ($CO_2$) [29] where occupant behavior and the number of occupants within an indoor space has a specific negative effect on $CO_2$ levels [18]. Building occupants' behaviors influence these indoor climate factors, which require special attention when assessing IEQ conditions and determining the presence of adequate ventilation. [16]. 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, 23] has emerged as a notable area of study, emphasizing the creation of physical data visualizations, making the invisible tangible and interactable by encoding data in physical artifacts [39]. This shift from focusing on individual artifacts in broader environmental context facilitates the physical embodiment of computing [15]. Data physicalization has the potential to positively influence the perception and exploration of data [23, 50, 54], presenting distinct advantages over traditional 'screen-focused' data representations, such as 2D canvas displays (e.g, digital web-based dashboards, screens within the room) [20, 22], 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 are frequently employed as persuasive technology, strategically designed to nudge individuals toward gentle behavior change leveraging the emerging notion of pervasive sensing to subtly enhance users' awareness regarding the impacts of their decisions [7, 40]. 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 [42] shows that only several ($f$=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 a large-scale architectural intervention which 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 [25, 57].

This mixed-methods approach (both qualitative and quantitative) helps understand occupants' needs and informs the design and the technical set-up of the prototype evaluating the effectiveness by focusing on the user's needs from the start of the study [34, 41]. In the first phase, an online questionnaire was conducted to *understand* occupants' awareness of indoor air quality (see Section 3.2). For the second phase, IAQ monitors are installed within meeting rooms for *data collection* and to 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). In the last phase participants *evaluated* the prototype and performed usability tests (see Section 3.5). Before setting up the survey, creating the prototype, and conducting the evaluation interviews, the investigation focused on the concepts of indoor air quality monitoring and data physicalization through a literature review and desk research.

### 3.1 Case study building

This study is 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.

### 3.2 Questionnaire survey

To understand and collect occupants' subjective awareness and satisfaction with IAQ, a structured survey gathered quantitative data within the building as a form of Post Occupancy Evaluation (POE) (see Appendix N).

*3.2.1 Questions.* The questions draws from two POE studies with a focus on indoor air quality [45, 46] usng 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 nine 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.* Handouts with QR Codes to the survey are distributed to occupants present at the informal learning spaces of the atrium, first, and second floors, using eligibility criteria based on demographic characteristics. 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.

*3.2.3 Responses.* The survey was open for submission for eight weeks, from March 1 $^{st}$ to April 31$^{st}$, 2024 which recorded 32 responses in total, of which after cleanup, a total of 29 (*n*=29) responses were included in the final dataset. The survey did not collect any personally identifiable information, such as age and gender, and it adhered to ethical considerations (e.g., consent forms). 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).

*3.2.4 Data cleaning, preprocessing and analysis.* Following the survey distribution, data analysis involved cleaning the data (e.g., removing non-consenting users) using Python's Jupyter Notebook format [6] and visualizing insights with tools like Seaborn [7]. This process included creating graphs and plots (e.g., boxplots of Likert scales) to gain an overview and understanding of the occupants' perspectives.

[3]https://uva-dilab.com/
[4]https://lab42.uva.nl/
[5]https://www.amsterdamsciencepark.nl/
[6]https://jupyter.org/
[7]https://seaborn.pydata.org/

## 3.3 Air Quality Monitoring

To gather data about the current air quality situation within the building, IAQ monitors were retrofitted to two specific meeting rooms (see Appendix G). This collected data further informed and provided the basis for inputting data into the data physicalization process.

*3.3.1 Technical set-up.* Monitors were deployed in meeting rooms regularly used by occupants to understand their behavior and perception in real-world corporate settings rather than controlled lab environments. These rooms are referred to as the small room (Room A), measuring 18 $m^2$ and typically accommodating small meetings with seven seats, and the large room (Room B), measuring 48 $m^2$ and suitable for larger meetings and seminars with fourteen seats. Two commercially available indoor climate data loggers were installed using 3D-printed mounting plates: an AirCheq Touch Aero [8] in the smaller room and an Atal ATU-CT ClimaTrend [9] in the larger room. Both monitors utilize industry-standard sensors from manufacturers like Senseirion and SenseAir to measure common pollutants. They were mounted (between 80cm and 120cm from the ground) and calibrated (intervals and polling rates) according to the installation manuals provided by the manufacturers. The monitoring devices operated for four weeks, from April 1$^{st}$ to April 30$^{th}$.

*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 ($CO_2$) (see Appendix M). The data logs were cross-referenced with weekly schedules derived from the internal booking systems of the rooms. This alignment was based on timestamped data to synchronize sensor values with scheduled meetings. Data analysis followed a procedure similar to that described in (see Section 3.2.4). The data underwent cleaning to remove entries primarily from non-opening hours and was then plotted and visualized to explore patterns and cross-referenced with meeting times.

## 3.4 Ideation and requirements

As a starting point for creating a physical representation of the air quality data, the formative research is grounded in the growing interest in establishing theoretical and design foundations for *data physicalisation* [8, 20, 42] on how to encode the properties and use a common design language [39, 47] established by systematic reviews of data physicalization projects. The creation of a prototype (see Figure 2) illustrates the technology to be and are often deployed to conduct lab experiments and case studies [25]. The following definition describes the overall goal of the physicalization:

> *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 aim of the prototype is to gather knowledge about the intervention and human behavior around it, aligning with a pragmatist methodology in design research where methods adapt and evolve through interactions with participants. Before prototyping the design solution, the overall requirements and scope of the physicalization and case studies used for ideation are described. The final prototype is then described based on the encoded variables and design dimensions found in the literature (see Section 4.3).

*3.4.1 Concept requirements.* Based on this scope and the survey, the concept requirements ("r" for "requirements") of the design solution are described in further detail, prioritizing six overarching requirements ranked using 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 ideation.* In developing the concept models, two existing datasets of academic and non-academic case studies served as comparative studies and for desk research, providing a starting point for ideation. First was the DataPhys gallery [10], a collection of 372 entries classified as data physicalizations. The second was

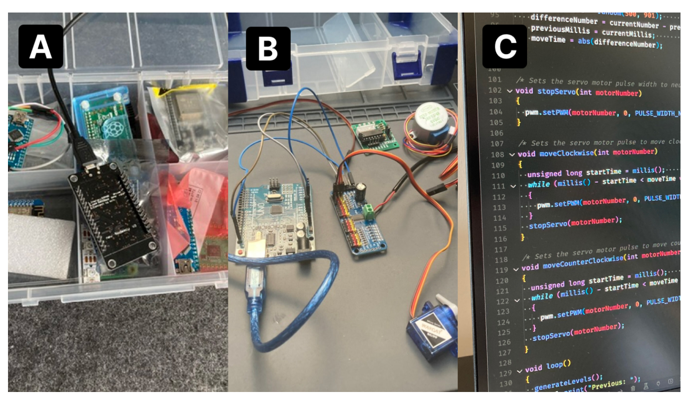


**Figure 2: Impressions of the prototyping and ideations phase. A) Gateway device B) Testing servo motors C) Writing firmware code**

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

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, which consisted of both academic and non-academic samples [4, 39, 42]. Out of these, ten ($f$=10) samples of academic work 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 X). Additionally, twenty-four ($f$=24) 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 Y). The aim was to find samples and design solutions that focussed on ambient interaction and had similar social contexts. This analysis led to a better conceptualizing of the design based on the aforementioned requirements of the data physicalization.

*3.4.3 Concept models.* Based on the user requirements and ideation three low-fidelity (lo-fi) concepts were further elaborated (see Appendix W) to choose one to develop in high fidelity (hi-fi) for user studies and evaluation. For this concepting, methods from the Communication and Multimedia Design (CMD) Methods Pack [11] and Design Method Toolkit [12] by the Digital Society School (DSS) were used.

Concept selection was based on weighted physicalization criteria from the literature, a Harris profile for the lo-fi concepts, and feedback from researchers with HCI and data visualization backgrounds ($n$=6 researchers not involved in the project, see Appendix C). 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 Appendix J).

## 3.5 Evaluation

A field-based evaluation approach within a meeting room of the Lab42 building was employed, utilizing methods from the Human-centered Design Kit by Ideo [13] and the Delft Design Guide from Delft University of Technology (TU) [14]. For evaluation criteria, the intentions and evaluating interview methodology described in the data physicalization design vocabulary [22, 39] are used 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, questions were adopted and rewritten from the Technology Acceptance Model (TAM), Software Usability Measurement Inventory (SUMI), and System Usability Scale (SUS) to gather insight into perceived usefulness, attitude towards use, and system usability [11, 14]. These questions served as a baseline and starting point but were revised and adapted 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 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: **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 five ($n$=5) and accepted because the study findings reached theoretical saturation, new interviews did not yield new insights after the first four interviews which led to repetitive data [49]. 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. 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 2 days per week

These criteria ensured that participants were familiar with the interior design of the building and meeting rooms, allowing them to provide contextually relevant feedback. This facilitates more granular follow-up questions and provides context for discussing the prototype. This resulted in a sample of 5 participants ($n$=5) consisting of various roles and education levels (such as Software Engineering, Multimedia Design and Web Development). Participants used the meeting rooms on average one ($f$=1) time per week and worked within the lab42 building on average three ($n$=3) ($min$=1, $max$=5, $mdn$=3) days a week. On average, an evaluation session took a total of 50 minutes. The evaluation session where held between May 24th and 14th of June 2024.

*3.5.3 Evaluation interviews.* Within the meeting room (sitting down) in the presence of the developed prototyped pre-arranged (installed in situ), 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.

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

The participants were not primed in advance about the concept of the prototype to explore how the building occupants understand and use the prototype and 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 (standing up), stating anything they noticed (encouraging probing strategy). Participants' usuallybehavior 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 form consisting of five statements rated on a Likert scale from one (strongly disagree) to five (strongly agree) to evaluate several properties of the prototype for their effectiveness (see Appendix S). During the evaluation session, the participants filled out the survey on a researcher's laptop (sitting down). 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 [15] to avoid bias while note-taking. The transcribed interviews as textual data were processed via Atlas.ti [16] for explorative qualitative coding to categorize and label possible design recommendations and improvements.

## 4 RESULTS

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 survey responses indicate that occupants have limited awareness of IAQ but generally perceive it as acceptable (see Figure 3). This perception is attributed mainly to the building's spacious open areas and the presence of planters, which collectively contribute to satisfactory IAQ levels.

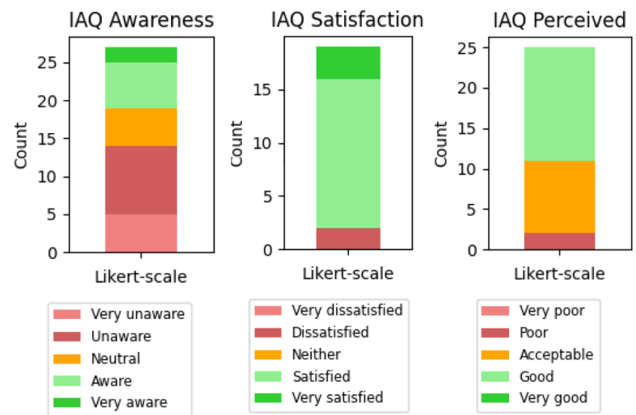


**Figure 3: Likert scales of IAQ awareness, perception and satisfaction of the questionnaire survey with occupant count**

*4.1.1 Activity and occupancy.* The first set of survey questions focused on activity and occupancy within the Lab42 building. On average, respondents used the Lab42 building three times per week for various activities (*min*=1, *max*=5, *mdn*=3). Usage varied, with some occupants frequenting the building only once per week while others used it all five working days per week. Most survey respondents were located on the ground floor ($f$=10) and the first floor ($f$=15), as opposed to the second floor. This is by design of the building where the ground and first floors are designated as the 'open area' and part of the atrium, which are designed for informal co-working and learning spaces. Most occupants described the overall occupancy as moderate ($f$=16), with fewer stating it was either crowded or not crowded at all.

*4.1.2 Awareness, satisfaction and perception.* The second set of questions involved three Likert scales assessing perceived IAQ, awareness of IAQ, and satisfaction with IAQ. Over half of the occupants reported low awareness of IAQ in their current space, identifying as very unaware ($f$=5), unaware ($f$=9), or neutral ($f$=5). Only a minority of occupants were aware or very aware of IAQ. Despite this low awareness, most occupants perceived the IAQ as acceptable ($f$=9) or good ($f$=14), with nearly all expressing satisfaction, either satisfied ($f$=8) or very satisfied ($f$=14).

*4.1.3 Health and cognitive symptons.* The third set of questions aimed to identify if users experienced health or cognitive symptoms related to IAQ. The majority of participants reported no health ($f$=21) or cognitive ($f$=15) symptoms. A small percentage experienced health issues such as headaches and nausea, while a larger percentage reported cognitive symptoms like difficulty focusing or fatigue. These results are inconclusive, as linking these symptoms to IAQ directly is challenging.

*4.1.4 Open-ended air quality description.* The open-ended responses revealed that many occupants perceived the IAQ positively, often attributing this to the openness of the atrium space. For instance:

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

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

*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."*

Additionally, many occupants mentioned the presence of hanging planters and greenery as factors contributing to their perception of sufficient IAQ:

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

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

These qualitative insights underscore the importance of spatial design and greenery in influencing occupants' perceptions of IAQ.

## 4.2 Air Quality Monitors

The collected data logs were exported from the monitoring devices and analyzed with a primary focus on $CO_2$ concentrations, as this parameter significantly impacts indoor air quality (IAQ). $CO_2$ levels accumulate due to human respiration, and air quality is heavily influenced by room occupancy. The analysis of these logs reveals occupancy patterns typical of scheduled meetings and the development of suboptimal $CO_2$ concentrations within the meeting rooms frequently exceeding the optimal threshold of 600 *ppm* (see Appendix P).

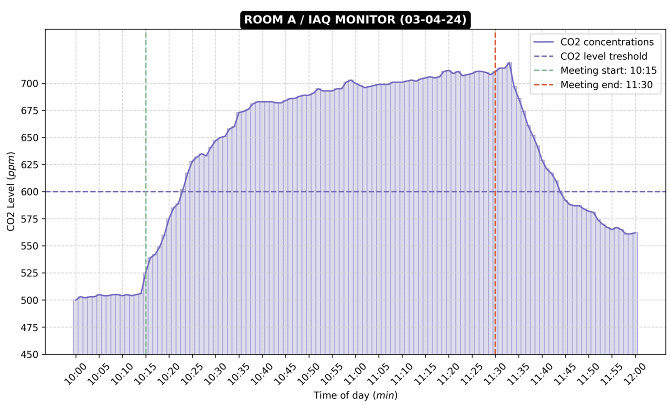


**Figure 4: Line chart of a single meeting in the small Room A showing the start and end time of the meeting**

*4.2.1 Single meeting $CO_2$ development.* A sample of $CO_2$ concentrations (see Figure 4) in a single meeting shows $CO_2$ levels over time, with the x-axis indicating time in minutes and the y-axis showing $CO_2$ concentrations in ppm. The ideal maximum threshold of 600 *ppm* is marked on the x-axis. Two colored lines on the y-axis denote the start and end times of the meeting. The data indicates that within fifteen minutes of the meeting starting, $CO_2$ levels reach suboptimal levels and continue to rise, stabilizing around 950 *ppm*, which is the peak concentration for the meeting. Continuous exposure to $CO_2$ levels between 800 *ppm* and 1000 *ppm*, or higher is considered detrimental to cognitive functions. After the meeting concluded, $CO_2$ concentrations gradually decreased to the baseline level of 450 *ppm* as occupants left the room.

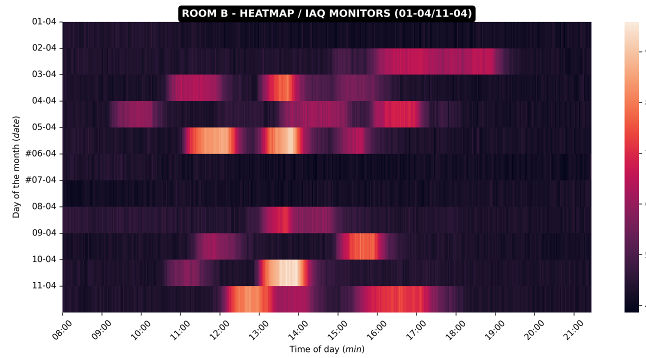


**Figure 5: Heatmap of ten days of data logs from Room B showing the peaks of $CO_2$ concentrations monitored**

*4.2.2 Regular day $CO_2$ development.* The visualization in Appendix P depicts $CO_2$ concentration spikes throughout a typical day with multiple meetings. The x-axis plots $CO_2$ levels, while the y-axis represents the full day within the building's opening hours. Data from randomly sampled days show that most meetings occur between late morning (11:00) and late afternoon (17:00), roughly two hours after the building opens and four hours before it closes. There are outliers, with some meetings occurring early in the morning right after opening and occasionally extending into the evening.

*4.2.3 Meeting schedule $CO_2$ development.* A heatmap of ten days of $CO_2$ concentration monitoring (see Figure 5) reveals that typically two or three meetings occur each day, usually lasting around one hour. Most of these meetings result in $CO_2$ levels exceeding the 600 ppm threshold. Line plots and heatmaps suggest that Room B, being larger, is more frequently used and reaches higher $CO_2$ concentrations. However, these results lack conclusiveness because they depend on the specific context and periods during which data was collected and monitors were installed.

## 4.3 Prototype

Based on the requirements, data physicalization design principles, and exploration of concept models, a high-fidelity (hi-fi) prototype was developed. This prototype serves as a proof-of-concept for the physical design solution and was used in the user study for evaluation.

*4.3.1 Concept description.* The prototype, named *Bluebird*, is a hanging kinetic sculpture inspired by natural materials and the shapes of hanging planters. It encodes indoor air quality (IAQ) data to foster a relationship with nature. Designed to be hung from the ceiling in small to medium-sized rooms, it changes based on real-time air quality data, engaging occupants with the air quality levels. The artefact features strings (representing plant branches) that elongate or contract, simulating plant growth, and leaves that move to indicate air freshness and movement. The design philosophy employs calm technology to minimize interruption costs [12]. Unlike existing solutions, Bluebird provides predictions and historical data, not just feedback on current conditions when $CO_2$ levels are high.

4.3.2 *Experimental set-up.* The prototype was installed *in situ* in one of the meeting rooms in the building (see Figure 6). Four dimensions were derived from the literature to describe the prototype: *properties, environment, interaction, and representation* [4, 20, 42].

- **Properties**: The technology-assisted physicalization uses explicit visual variables such as size, position, timing, and movement where occupants visually see the strings becoming larger (height) and leaves moving to change the visual arrangement (movement), all based on the temporal frequency of $CO_2$ concentrations.
- **Environment**: The design uses associative metaphors through shapes and movement, resembling organic forms found in nature (shape and form). It is a medium to large-scale (50 - 150 cm) physicalization, placed semi-publicly within the open building context.
- **Interaction**: The artifact communicates environmental data, aiding in understanding and encouraging reflection. It features indirect interaction, changing based on occupant activity.
- **Representation**: The dataset is dynamic, streaming real-time environmental data from building sensors and outputting categorical data on $CO_2$ concentration variations.

4.3.3 *Electronics and components.* The prototype is controlled by an Arduino Uno R3 [17] microcontroller with a PWM 6-Channel Servo Driver [18] operating six 360° MG90S type Micro Servo Motors [19]. These motors, attached to pulleys with paracord ropes, simulate plant growth by moving the strings up and down. All electronics are integrated into the back of a wooden board, making the device stand-alone, movable, and modular for installation in other spaces.

4.3.4 *Crafting technologies and materials.* The strings, leaves, and housings for the electronics and mechanical hardware were created using additive manufacturing (3D printing) with Fused Deposition Modeling (FDM) techniques a fabrication technique commonly found in data physicalizations [4]. Polylactic acid (PLA) plastic filament in various colors was used. The electronics enclosures and plant models were designed using computer-aided design (CAD) software. To create leaf-like representations, custom properties were defined in the 3D printing software (slicing) to remove top and bottom layers, resulting in a thin infill layer.

4.3.5 *System Architecture and software.* The microcontroller runs custom firmware written in Arduino code[20] (similar to C++), receiving real-time data from air quality monitors using the Lab42 internal building API (see Appendix L). Via an ESP32 (NodeMCU)[21], the data is sent over UART to the Arduino controller. 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 [21, 32]. Custom library functions were written to calculate string movements. The current ($C_{\text{current}}$ ) and $C_{\text{previous}}$ $CO_2$ concentrations are stored, with the difference calculated and mapped to a movement time $t_{\text{movement}}$ in milliseconds. Based on whether the integer is negative or positive and a multiplication factor, the servo motors spin either clockwise (growing) or counterclockwise (shrinking) the ropes.

## 4.4 Evaluation

The prototype-led evaluation sessions (see Section 3.5) assessed occupants' understanding of the data physicalization, usability, and effectiveness, providing insights for design improvements. The results describe the explorative coding of the transcribed interviews in relation to the hypothesis.

4.4.1 *Usefulness and aesthetic impressions (engagement).* All participants (see Appendix T) indicated during the usability test or through their scores that they enjoyed viewing the data physicalization and gained valuable insights about indoor air quality from its display in the meeting room. They also reported a high likelihood of taking preventive action based on these insights. Opinions on the materials and aesthetics were mixed: *P2* suggested adding more strings for granular data, while others found the current number sufficient. *P3* proposed more variation in the leaves' shapes and densities for aesthetics, but this was not a shared view. *P2*, *P3* and *P5* also recommended that the wooden board and materials be better integrated into the room's interior by hiding it in the ceiling or covering it to match the color scheme.

> *P4: "I also think the leaves are too artificial, I would prefer more organic materials. [..] The wooden board feels off [...]"*

4.4.2 *Perceived data and learnability (understanding).* Almost all participants, except for *P2*, indicated that the prototype's learnability on initial view is high. They noted that without clear instructions, the physicalization is too abstract in conveying information about indoor air quality, as reflected in generally low scores for statement S2 (see Appendix V) from the survey. Design recommendations mostly evolved around helping occupants better understand the physicalization with better onboarding for example, in the form of a scannable QR code or text instructions on the wooden board.

> *P1: "[...] on initial view it's a bit of a puzzle what IAQ properties it communicates. But once you understand it and learn it I assume it will have a long-term behavior change effect."*

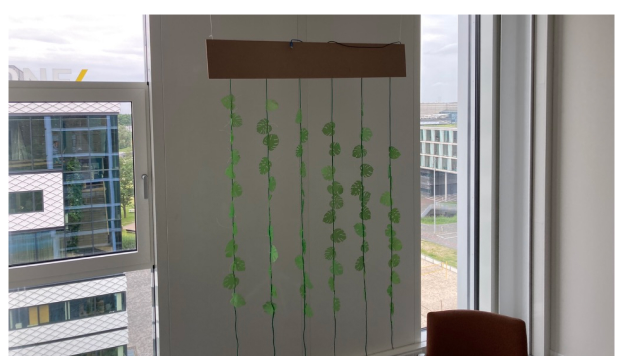

**Figure 6: Photograph of the prototype installed in the room during an evaluation session with a participant**

[17] https://store.arduino.cc/products/arduino-uno-rev3
[18] https://learn.adafruit.com/16-channel-pwm-servo-driver?view=all
[19] https://www.towerpro.com.tw/product/mg90s-3/
[20] https://www.arduino.cc/reference/en/
[21] https://www.nodemcu.com/

#### 4.4.3 Design Improvements and recommendations (effectiveness).

Participants suggested numerous design improvements and recommendations during usability testing. These suggestions, coded and categorized, primarily aimed to increase the physicalization's overall effectiveness (see Appendix U). *P1, P2, and P3* emphasized that the positioning of the physicalization within the room significantly impacts its effectiveness for all occupants. Additionally, *P1, P3, and P5* recommended color-coding or labeling the leaves indicating the history, current, and future predictions of $CO_2$ concentrations to make this property more apparent.

> *P3: "I feel like the positioning within the room is important. [...] You want the physicalization visible to all occupants within the room. Putting it next to the door or one wall makes people sit with their back to it."*

# 5 DISCUSSION

An examination of the grounded theory research design and methodologies utilized in this study combined with an interpretation of both qualitative and quantitative findings reveal several comparative findings, study limitations, and opportunities for future research.

## 5.1 Findings in context

Comparing the findings of the existing literature (see Section 2) the results of this study (see Section 4) shows that general findings from the literature are supported. A key distinction lies in this study's human-centered design approach, which incorporated occupants' feedback throughout the iterative research process. The findings from one methodology informed decisions on subsequent approaches in the study (see Section 3). Furthermore, it is important to note that these comparative studies vary significantly in their context (e.g., outdoor environments) and lab settings (e.g., households).

#### 5.1.1 Occupant awareness and IAQ monitor.

Occupant awareness of indoor air quality (IAQ) is generally low (SQ1) due to its inherent properties, making it difficult to detect through human sensory perception. Occupants often judge indoor air quality based on visible attributes within the environment, which usually do not positively influence air quality [44] [13]. Building activity, occupancy, and crowdedness significantly impacts the accumulation of $CO_2$ concentrations (SQ2), the primary factor of suboptimal air quality in indoor environments [18] [16], especially in smaller spaces like offices and meeting rooms [56].

#### 5.1.2 Prototype development and evaluation.

The additional step undertaken in this study was the creation of the prototype which extends beyond the scope of previous related studies. The prototype's development employed techniques and manufacturing methods commonly used in data physicalization projects [3, 23], while its evaluation followed methodologies frequently applied in HCI research [39, 42]. Evaluation sessions indicated increased understanding and self-reflection regarding data insights and revealed several design improvements for the prototype (SQ3). However, no significant effect or success rates were measured of the prototype's ability to help occupants take preventive action for long-term behavioral change.

## 5.2 Limitations

The data collection, design, and validation process showed several strengths but also had some limitations that should be noted. The primary limitations encountered during this study were the reproducibility of the evaluation sessions, monitoring validity prototype scalability and generalizability of findings to other buildings.

#### 5.2.1 Evaluation reproducibility.

Grounded theory is an established research method, but greater care and effort should have been taken for investigator and theory triangulation. Some concepts may have been missed during the ideation phase since only the main researcher was involved in the prototyping. During evaluation sessions, the lack of four-eyed principles left room for researcher and interviewee biases. The small sample size, although it reached saturation, limited generalizability, and demographic diversity. A more varied interview setting, such as different-sized meeting rooms or personal office spaces, could have tested usability in diverse contexts. The same group of participants was used for both interviews and the user study, potentially biasing their evaluations. And while this study used similar approaches to others, including HCI evaluation and SUS metrics, the methods were slightly adapted, impacting the reproducibility and the validity of standardized quantitative results.

#### 5.2.2 Prototype scalability.

The prototype used in user studies is a proof of concept but requires further optimization. Concessions were made due to limitations in hardware availability and technical data constraints. Design improvements are prevalent, acknowledging that there is no universally perfect way to display air quality data. The prototype's current appearance can influence its effectiveness as users might perceive it as non-finished. A significant limitation is the inability of the current setup to explore long-term intervention strategies due to the need for testing over an extended period.

#### 5.2.3 Building generalizability.

The methodologies employed within Lab42 and its specific context may limit generalizability to other buildings and environments with different characteristics. The building's unique environmental properties (furniture, room allocation) contribute to this context. This also means there is an inherent bias in the user group, despite voluntary and random survey and interview distribution, convenience sampling for participant recruitment may introduce a bias toward higher-educated university students and staff members present in specific areas of the building, causing a higher attrition rate, which may not be representative of a larger population.

#### 5.2.4 Data collection validity.

Care was taken using standardized high-quality sensors and the well-defined data collection procedures ensured reliability, monitoring within meeting rooms primarily focused on environmental properties like $CO_2$ concentrations, lacking explicit data on occupancy. Adding more context to interpret occupant behavior and $CO_2$ concentration patterns, as well as considering the effects of existing mechanical ventilation could enhance the data collection phase.

### 5.3 Future work

Future research should prioritize enhancing the design and communicative properties of the prototype, along with implementing a more structured lab environment to gather quantifiable results on its effectiveness and its support in long-term preventive action among occupants.

*5.3.1 Design enhancements.* Enhancements to the prototype include communicating additional sensory properties, such as conveying humidity through organic materials like fabric and color-coding leaves to better illustrate predictions and enhance the perception of fresh air. Incorporating more material-driven feedback aims to deepen engagement and foster embodied, multi-sensory experiences.

*5.3.2 Long-term effectiveness.* Evaluating the prototype's efficacy beyond initial impressions requires addressing validity and control measures for concrete effectiveness assessments, possibly through broader behavioral data collection in daily life scenarios, possibly by incorporating window sensors to track occupants' window usage during meetings. To ensure the generalizability of findings, replication across diverse environments is essential. Replicating the study in multiple buildings with diverse occupants would strengthen the generalizability of results, given the unique characteristics of Lab42, including its architecture and occupant demographics.

## 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 IAQ, correlates this with air quality monitoring data, and explores how physically communicating these properties can increase data insights and serve as an intervention strategy. Findings reveal occupants' general unawareness of IAQ, often judging it based on visual aspects of the indoor space. Monitoring $CO_2$ levels in meeting rooms indicate frequent suboptimal thresholds, posing health and cognitive risks. The developed prototype and its evaluation suggests a positive attitude toward interpreting IAQ data and taking preventive actions, albeit with preliminary indications lacking statistical significance and long-term effectiveness results.

Limitations include the specific context of the university building affecting generalizability and the methods used to evaluate the prototype limiting the reproducibility and quantifiable metrics. Future research should verify findings in diverse settings with a more rigorous long-term lab environment and enhance the prototype's design and aesthetics for multi-sensory interaction, possibly enhancing the effectiveness of its physicalization properties. Ultimately this study establishes a foundation for future research within the niche of data physicalization addressing the research gap in understanding occupants' behavior to take preventive actions based on their indoor environment. It contributes to Human-Building Interaction by integrating computing technologies into built environments, assisting building staff and responsive architecture in optimizing space design to enhance occupants' 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, further expanding 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) [22] 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 [23] and Campus Rules and Policies [24].

## Appendix C DOMAIN EXPERT VALIDITY AND PILOT TESTS

Before conducting the questionnaire survey, data gathering process, and interview evaluation procedures, domain experts from the Informatics Institute [25] and the Digital Interactions Lab (DIL) [26] at the University of Amsterdam reviewed the methodology procedures. Draft versions of the questions and techniques were sent out to the supervisors and researchers from the lab for internal feedback. Then, the questionnaire survey and evaluation interview procedure were pilot-tested and after, several iterations, more widely distributed to occupants and open for participation. The research was presented during two internal 'lab meetings'. First, a brainstorming workshop was held with the concept diagrams of the prototype for expert review, and second, the final proof-of-concept prototype was presented for feedback and design improvements.

## 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) [27] from the University of Amsterdam. All occupant data was anonymized before publishing and nothing that can be considered personal data was collected. Data is stored on cloud service providers provided by the University of Amsterdam, such as Research Drive [28]. 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 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 [29], 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 setup: https://github.com/viszlab/

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

## Appendix G FLOORPLAN AND LAB SET-UP

A floorplan diagram (see Figure 7) provides an overview of the technical lab setup of the small (Room A) and large (Room B) meeting rooms used for indoor air quality monitoring. The floorplan indicates the position where monitors are installed and the position of doors and windows.

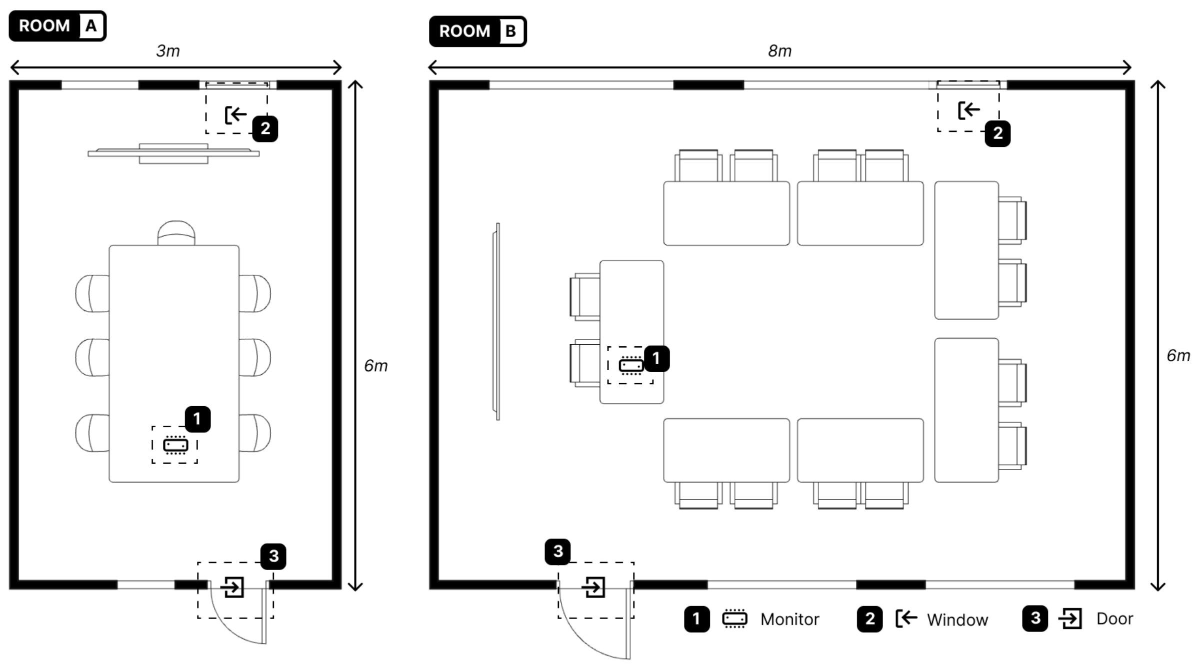



**Figure 7: Floorplan of Room A and B, monitors installed as of manufacturer specifications**

## Appendix H MEETING ROOM IMPRESSIONS

Photographs of the small (Room A, see Figure 8) and large (Room B, see Figure 9) meeting rooms taken from the viewpoint of the entrance of the door. It shows the default interior design set-up of the rooms and the position of the chairs and tables.

**Figure 8: The 'smaller'(18$m2$) space labeled Room A**

**Figure 9: The 'larger' (48$m2$) space labeled Room B**

## Appendix I BUILDING IMPRESSIONS

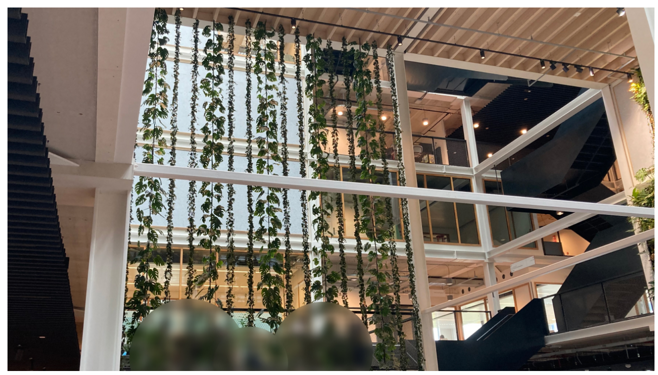
Photographs of the Lab42 building's interior and exterior showcase its strategically organized zones for individual and collaborative work. The interior design theme blends 'tech' and 'nature' to create a fresh, light, and warm ambiance.


**(a) West view of the Lab42 exterior**


**(b) Main entrance of the Lab42 exterior**

**Figure 10: Photographs of the Lab42 building from the outside**

**(a) Wall planters in the center hall**



**(b) Hanging planters in the collaborative working spaces**

**Figure 11: Photographs of the main entrance hall atrium**

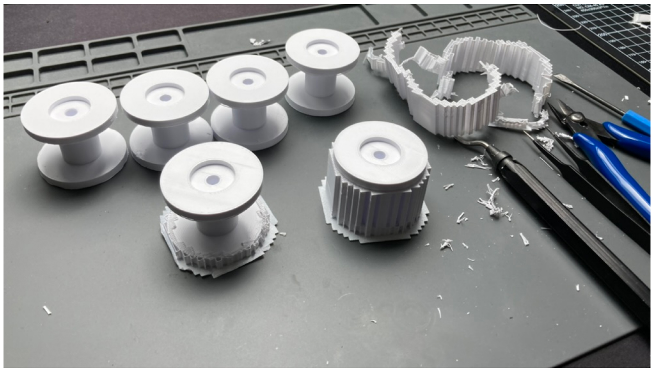
**(a) Informal working space on 2th floor**

**(b) Informal working space on the 1th floor**

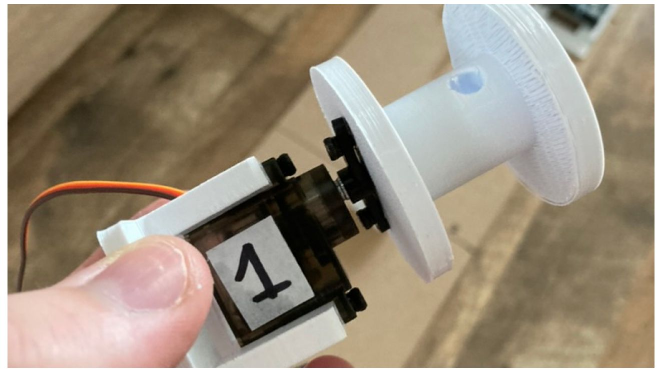
**Figure 12: Photographs of working space on the first floors of the building**

## Appendix J PROTOTYPE IMPRESSIONS

Photographs of the prototype-creating phase showing the manufacturing of the pulley mechanism (see Figure 13), fabricating the leaves (see Figure 14) and mounting the electronics (see Figure 15) for the high-fidelity data physicalization prototype.



**(a) Cleaning and sanding the 3D printed pulleys**



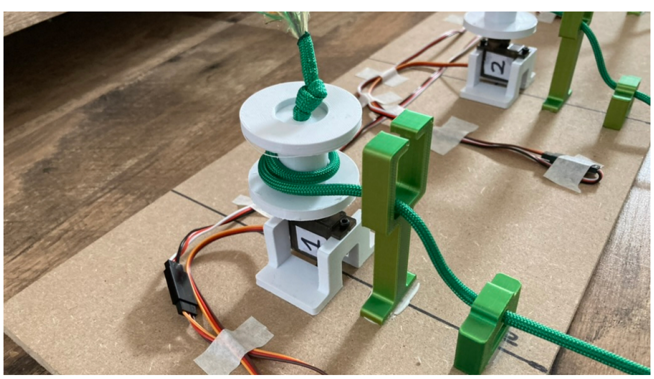

**(b) Attaching pulleys to servo motors using motor arms**

**Figure 13: The pull-up and down mechanism of the hanging planter strings**

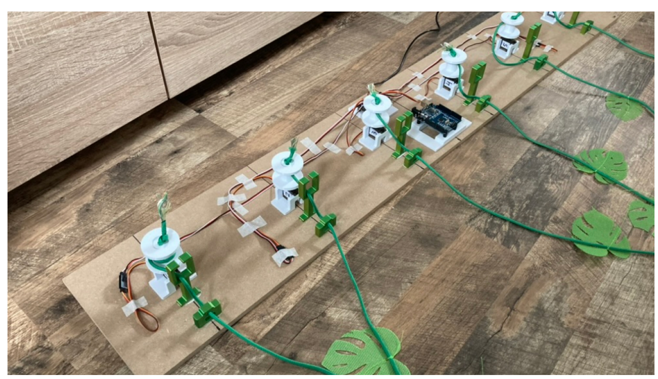

**(a) FDM 3D printer printing the textile leaves**

**(b) Attaching the leaves with fishing line**

**Figure 14: Hanging planter strings attached to the paracord**




**(a) Pulley mechanism installed with rope guides**



**(b) Attaching the electronics to the wooden board**

**Figure 15: Rear view of the prototype with all components mounted**

## Appendix K SYSTEM ARCHITECTURE OF THE PROTOTYPE

System architecture diagram (see Figure 16), which shows the Internet of Things (IoT) architecture of the prototype following the notion of edge computing using a 1) sensing layer, 2) networking layer, 3) processing layer, and 4) application layer.

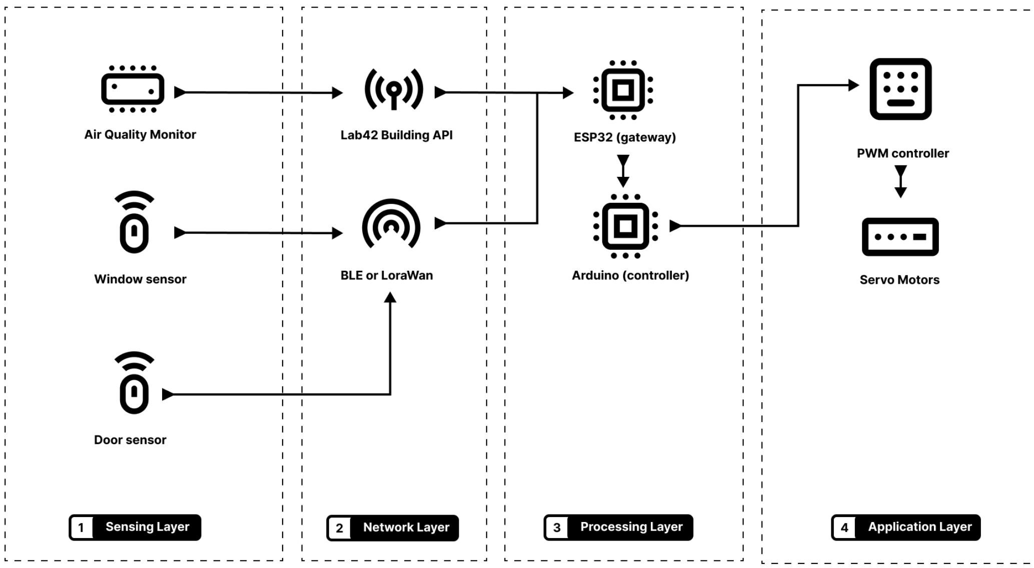



**Figure 16: System diagram that shows the technical set-up of the prototype**

## Appendix L LAB42 API SAMPLE DATA

A screenshot of the internal Lab42 building API documentation (see Figure 17). The API offers access to reliable and detailed sensor data installed throughout the Lab42 building at Science Park. Designed as a research resource for university employees and students. The available sensors in a specific room can be gathered through a Room ID, and data can be requested based on a specific date and timeframe.

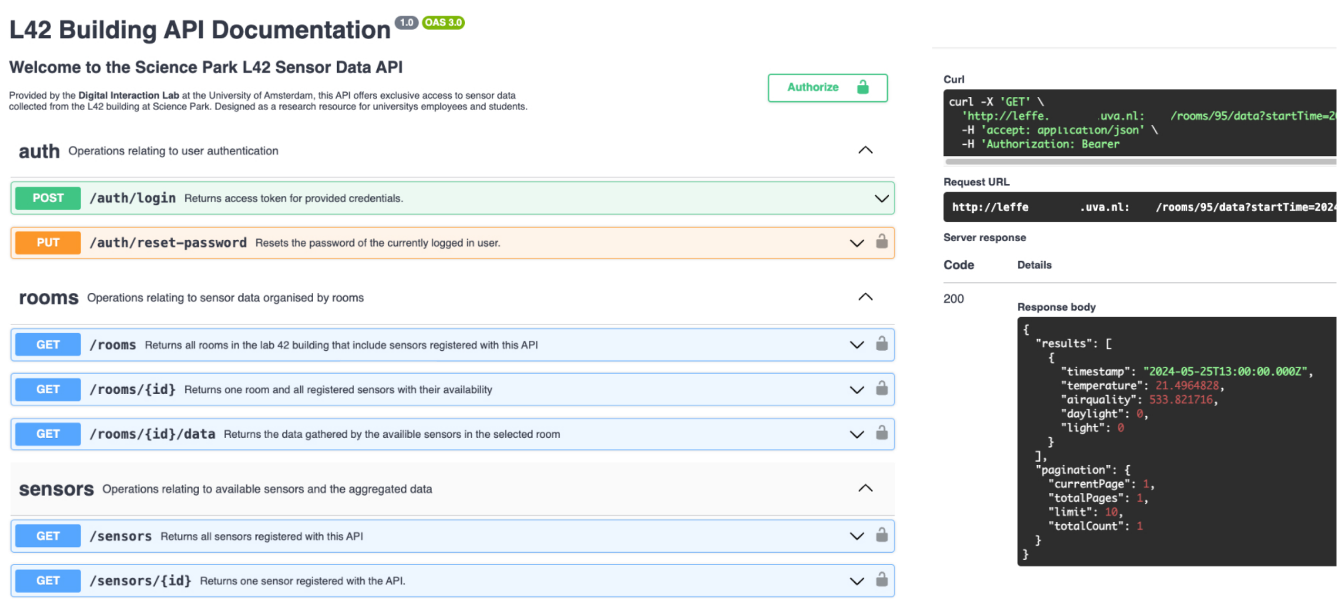



**Figure 17: Screenshot of the Lab42 building API documentation and sample data output log**

## Appendix M AIR QUALITY MONITORS SAMPLE DATA

Sample data logs (see Table 1 and Table 2 ) of the indoor air quality monitor devices installed in the small and large meeting rooms. These data logs were stored on-device during the data collection phase and exported for analysis. Both devices used the same polling rate but differed in the sensory readings the device was capable of. Both have data and timestamps, $CO_2$ concentrations, temperature, and humidity, which were used for the scope of this research.

| Date | Time | $CO_2$ | 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 |

**Table 1: Sample data log of the Aircheq Touch Aero installed in the 'small' Room A**

| Date | Time | Temp | RH | DewPoint | $CO_2$ | - | - | - | - | - |
|---|---|---|---|---|---|---|---|---|---|---|
| 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 with 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*

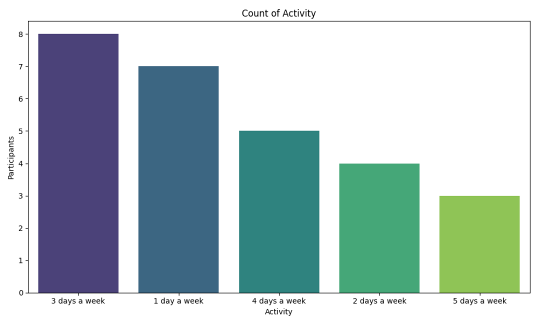
- None
- Headaches
- Trouble breathing
- Feeling nauseating
- Other

**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*

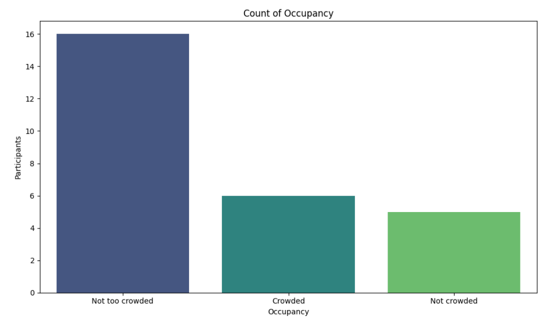
- None
- Trouble with focus
- Decreased productivity
- Tiredness
- Other

## Appendix O SURVEY DATA

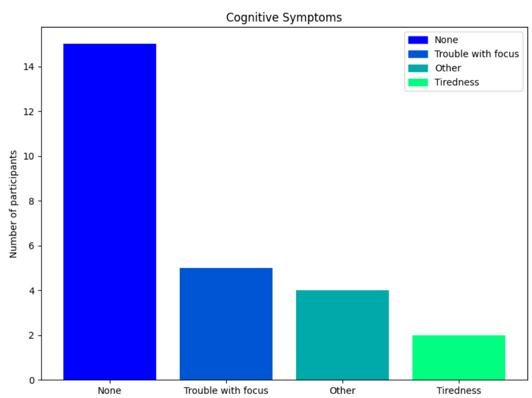
Plots for specific questions of the survey questionnaire data exported from Qualtrics. Bar charts are created to show the distribution of answers for each question (see Figure 18). The Likert scales are plotted as a stacked bar chart to show the scores (see Figure 19).



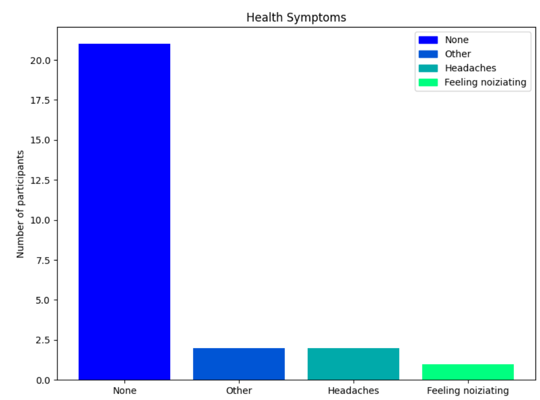

**(a) Average use of the building for various activities**




**(b) Description of occupancy crowdedness**

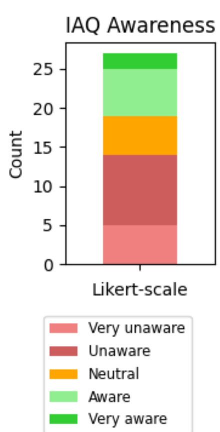



**(c) Cognitive symptoms based on the air quality**

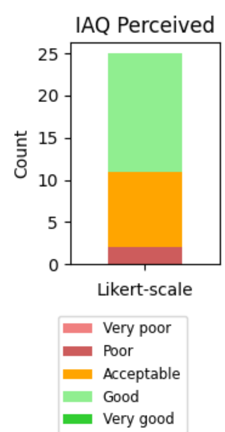



**(d) Health symptoms based on the air quality**

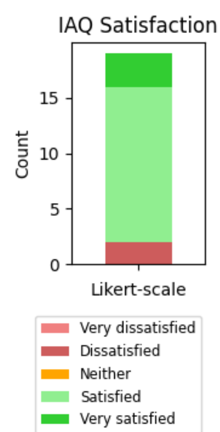
**Figure 18: Bar charts of the survey questions about activity, occupancy, health and cognitive symptoms**




**(a) IAQ Awareness**




**(b) IAQ Perceived**

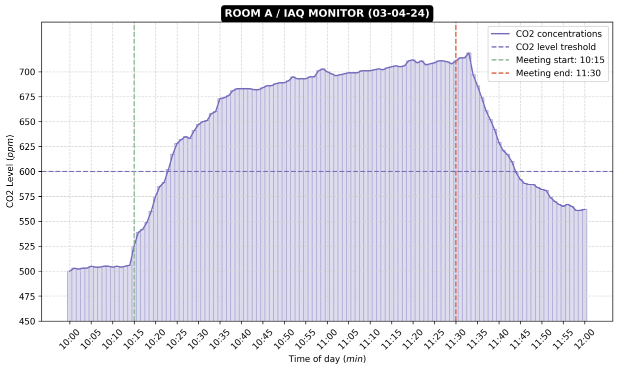



**(c) IAQ Satisfaction**

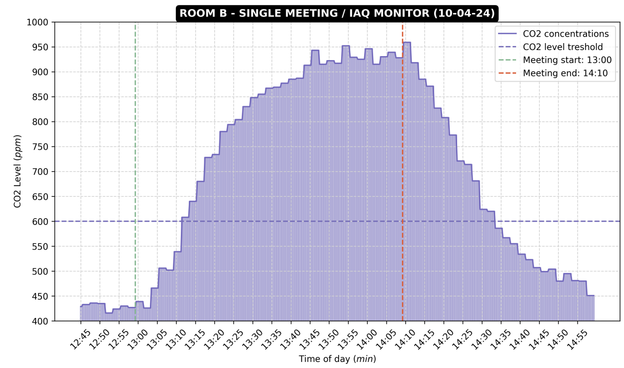
**Figure 19: Stacked bar charts of the Likert scales on IAQ awareness, perceived and satisfaction**

## Appendix P MONITOR DATA

Plots of the indoor air quality monitor data logs (see Figure 20, Figure 21, Figure 22). All graphs show the $CO_2$ concentrations in either the small (Room A) or large (Room B) meeting rooms. The plots are subsets of the data logs which show interesting patterns and peaks based on the observed timeframe of the data collection phase.

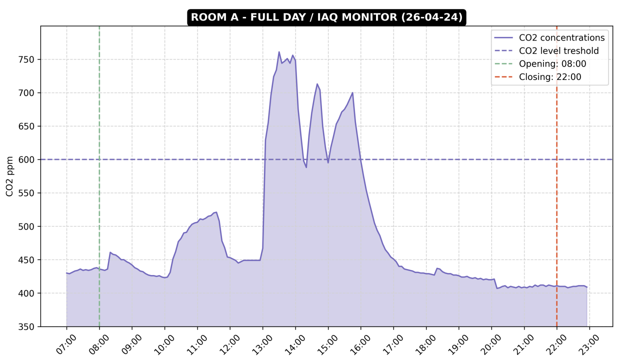



**(a) Single meeting $CO_2$ concentrations in Room A**

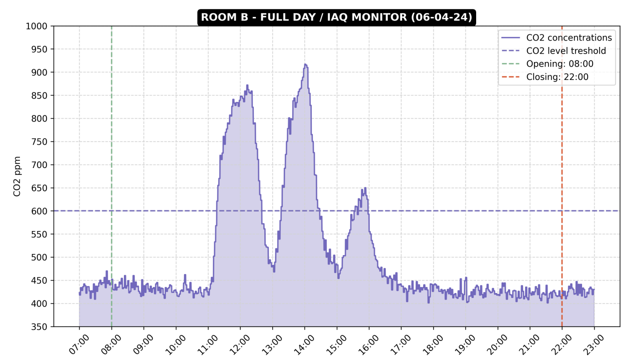



**(b) Single meeting $CO_2$ concentrations in Room B**

**Figure 20: IAQ monitoring $CO_2$ concentrations of a single sample meeting based on the start and end time of the meeting**

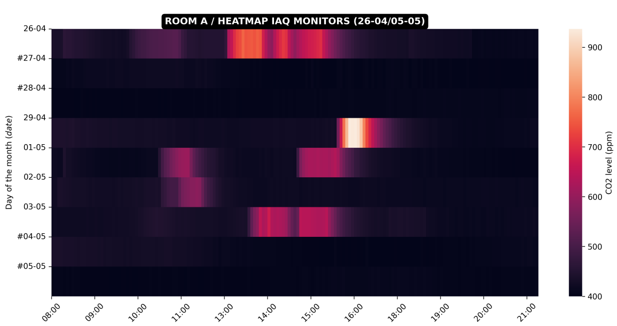



**(a) A day of meetings $CO_2$ concentrations in Room A**

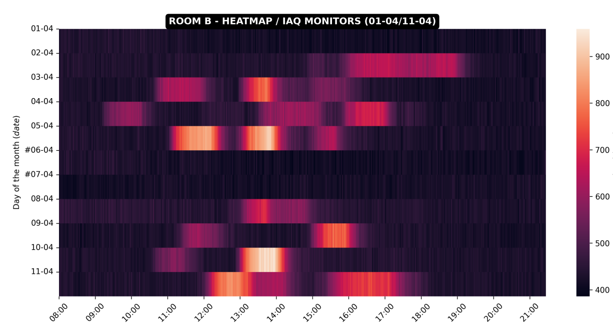



**(b) A day of meetings $CO_2$ concentrations in Room B**

**Figure 21: IAQ monitoring $CO_2$ 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 22: IAQ monitoring heatmap $CO_2$ concentrations of the sample ten days based on the opening hours of the building**

## Appendix Q EVALUATION INTERVIEWS

Semi-structured interview outline for the evaluation sessions conducted in English where the prototype is installed in situ within a meeting room on the sixth floor of the Lab42 building. The questions and structure below served as a guideline for the interviews and follow-up questions were asked based on the responses of the participants.

***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 5̃0 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?<br>**Q2:** What gender do you identify with?<br>**Q3:** What is your nationality?<br>**Q4:** What is your level of education? |
| Role of the occupant | **Q5:** What do you do in daily life for work?<br>**Q6:** How would you describe your role within this building?<br>**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?<br>**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?<br>**Q11:** On average how long is a typical meeting you attend?<br>**Q12:** What locations do you typically use for your meetings? |

**Question-set 3:** *Notion of indoor air quality (IAQ)*
**Introduction:** Lastly some questions 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?<br>**Q12:** How do you perceive the IAQ in this space? |
| Cognitive and health | **Q13:** Have you ever experienced cognitive symptoms related to IAQ in a meeting room?<br>**Q14:** Have you ever experienced health symptoms 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 observe its movements.

***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 hanging from the ceiling, a prototype of a physical artifact 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 artifact is? |
| Look and feel | **Q2:** What do you think of the overall design of the physical artifact? |
| Use of materials | **Q3:** What do you think of the materials the physical artifact 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 preventative 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?<br>**Q6:** How willingly are you to take preventative action based on the data insights the artifact 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

The occupant and researcher sit down on the table again and the occupant is handed the computer or phone of the researcher to fill in an online statement questionnaire on Qualtrics with Likert scales.

***Introduction:***
The last part is an online score rating statement and hypothesis about the prototype.

**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 EVALUATION PARTICIPANT SAMPLE

Sample size and demographics (see Table 3) of the participants who participated with their expertise and building activity.

| Participant | Gender | Age | Expertise | Education | Days in building | Working Space |
|---|---|---|---|---|---|---|
| P1 | Male | 27 | Web Developer | Bachelor | 2 days a week | Lab Office Space |
| P2 | Male | 23 | Software Engineer | Bachelor | 3 days a week | Learning spaces |
| P3 | Male | 25 | Software Engineer | Master | 3 days a week | Learning spaces |
| P4 | Male | 23 | Full stack developer | Bachelor | 2 days a week | Learning spaces |
| P5 | Male | 35 | Multimedia designer | Master | 4 days a week | Lab Office Space |

**Table 3: Participants sample of the evaluation sessions for demographics**

## Appendix U DESIGN IMPROVEMENTS AND RECOMMENDATIONS

Coding of main design improvements and recommendations (see Table 4) based on the feedback during the usability testing.

| Coding | Design Improvements (DI) | Design Recommendations (DR) | Category |
|---|---|---|---|
| DI-1 | Organic leaves and textures | Move from artificial plastic to organic plant material for strings and leaves, more variation in leaves and more string density | Material type |
| DI-2 | Hide electronics | Blend electronics housing more with interior design of room, or hide all together in ceiling | Design aesthetics |
| DI-3 | Provide instructions | Add instructions next to artifact withs scannable QR code or printed instructions board | Information |
| DI-4 | Label and color-coding | Label or color-code the strings to improve understanding, end balls to end of string to mark ending of data point | Data encoding |

**Table 4: Design Improvements and Recommendations**

## Appendix V STATEMENT LIKERT SCORES

Individual results of the statement scores in a table (see Table 5) and bar chart plot (see Figure 23).

| Participant | S1 | S2 | S3 | S4 | S5 | Average Score |
|---|---|---|---|---|---|---|
| P1 | 4.0 | 3.0 | 4.0 | 3.0 | 4.0 | 3.60 |
| P2 | 4.0 | 2.0 | 4.0 | 4.0 | 4.0 | 3.60 |
| P3 | 5.0 | 2.0 | 4.0 | 4.0 | 5.0 | 4.00 |
| P4 | 3.0 | 2.0 | 4.0 | 4.0 | 4.0 | 3.40 |
| P5 | 4.0 | 3.0 | 4.0 | 3.0 | 3.0 | 3.40 |
| **Average** | **4.00** | **2.40** | **4.00** | **3.60** | **4.00** | **3.60** |
| **Variance** | **0.50** | **0.30** | **0.00** | **0.30** | **0.50** | **0.064** |

**Table 5: Participant Scores, Averages, and Variance based on number of participants**

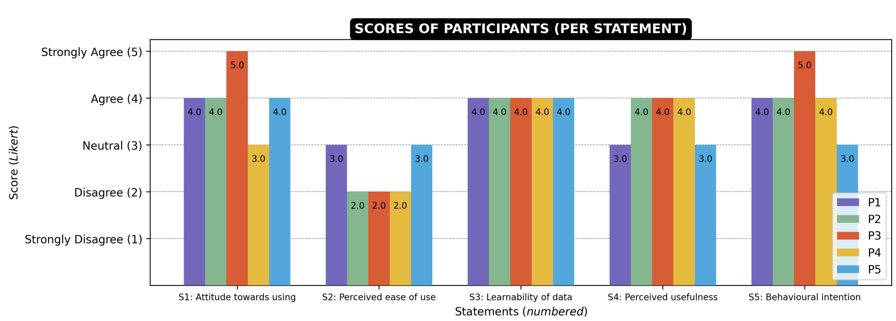



**Figure 23: 5-point Likert scales of participants per statement**

## Appendix W CONCEPT DIAGRAMS

Design diagrams (see Figure 24, Figure 25, Figure 26) 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.

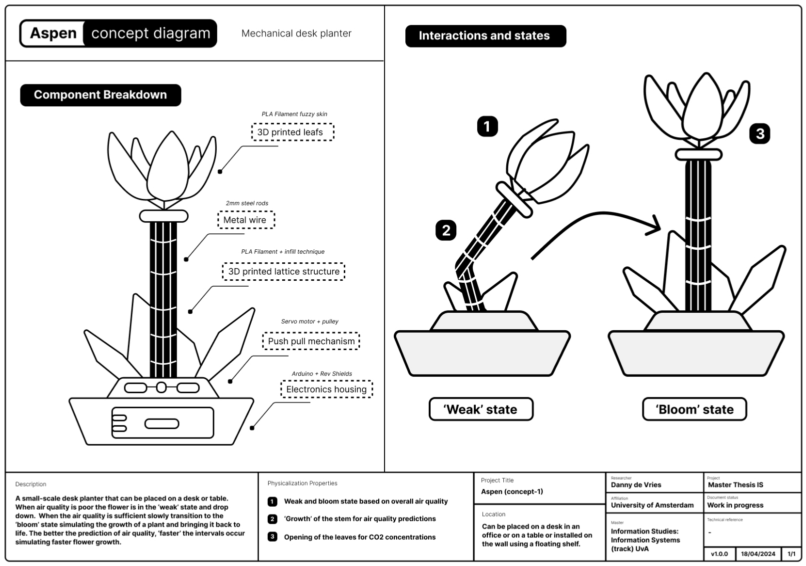



**Figure 24: Design diagram of concept one (Aspen)**

### 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, organic materials). Allows most interactivity. Taking inspiration from kinetic sculptures and hanging/floating sculptures.

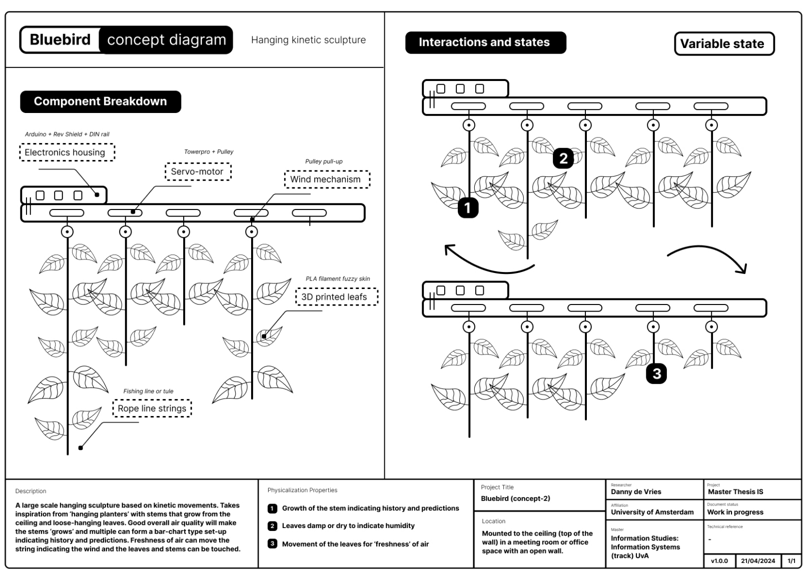



**Figure 25: Design diagram of concept two (Bluebird)**

**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.

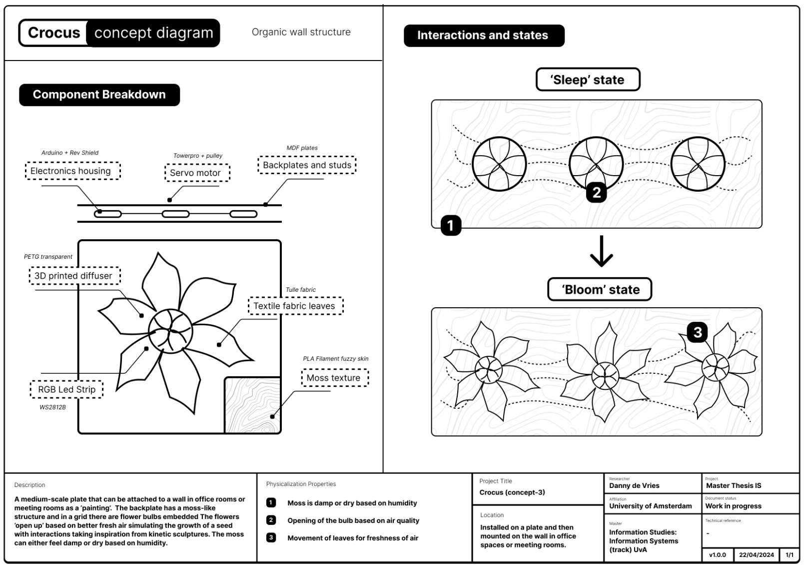



**Figure 26: Design diagram of concept three (Crocus)**

## Appendix X ACADEMIC SAMPLE CASE STUDIES

In the ideation phase and development of the concept models, an exploration of 10 academic case studies significantly influenced the design of the prototype. Table 6 provides an overview of all these case studies.

| Nr. | Sample | Author(s) | Year | Venue | Reference |
|---|---|---|---|---|---|
| 1 | Econundrum | Kim Sauvé et al. | 2020 | ACM | Econundrum |
| 2 | Caimform | Maxime Daniel et al. | 2019 | HAL | Caimform |
| 3 | Dataponics | Robert Cercós et al. | 2016 | DEG | Dataponics |
| 4 | Garden of Eden | Thorsten Kiesl et al. | 2007 | UFG | Garden of Eden |
| 5 | Pudica | Olivia Seow et al. | 2022 | MIT | 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 |

**Table 6: Overview of the 10 academic case studies used for the ideation phase and concept models.**

## Appendix Y NON-ACADEMIC SAMPLE CASE STUDIES

In the ideation phase and development of the concept models, an exploration of 24 non-academic case studies case studies significantly influenced the design of the prototype. Table 7 provides an overview of all these case studies.

| Nr. | Sample | Creator(s) | Year | Venue | Reference |
|---|---|---|---|---|---|
| 1 | Birdie Design | Birdie Design | 2024 | non-academic | Birdie Design |
| 2 | Tree of Ténéré | Studio Drift | 2017 | non-academic | Studio Drift |
| 3 | Petal Clouds | ART+COM | 2018 | non-academic | ART+COM |
| 4 | Electro Magnetic Field | Jennifer Allora | 2022 | non-academic | Arkive |
| 5 | Wind 3.0 | Studio Roosegaarde | 2011 | non-academic | Studio Roosegaarde |
| 6 | Floralis Generica | Eduardo Catalano | 2002 | non-academic | Plaza Unidas |
| 7 | Flylight | Studio Drift | 2013 | non-academic | Studio Drift |
| 8 | Spectra-2 | FIELD.IO | 2015 | non-academic | FIELD.IO |
| 9 | Meadow | Studio Drift | 2023 | non-academic | Studio Drift |
| 10 | Pet Lamp | Álvaro Catalán | 2024 | non-academic | Pet Lamp |
| 11 | Living map | Sigitas Guzauskas | 2018 | non-academic | Living map |
| 12 | Harassment plants | Nazareno Andrade | 2022 | non-academic | Harassment plants |
| 13 | Popsicles of Pollution | Hung Yi-Chen, | 2017 | non-academic | Popsicles of Pollution |
| 14 | Yellow Dust | C+arquitectos | 2017 | non-academic | Yellow Dust |
| 15 | Touching air | Miriam Quick | 2015 | non-academic | Touching air |
| 16 | Physical Weather Display | Ken Kawamoto | 2015 | non-academic | Physical Weather Display |
| 17 | Inequalities Quipu | Ewa Tuteja | 2021 | non-academic | Inequalities Quipu |
| 18 | Summer in the city | Carola Bartsch | 2015 | non-academic | Summer in the city |
| 19 | WeatherWindow | Tim Dye | 2014 | non-academic | WeatherWindow |
| 20 | Point cloud | James Leng | 2012 | non-academic | Point cloud |
| 21 | Tele-present water | David Bowen | 2011 | non-academic | Tele-present water |
| 22 | Real-time Warning | Rodrigo Medeiros | 2012 | non-academic | Real-time Warning |
| 23 | airFIELD | Dan Goods | 2012 | non-academic | airFIELD |
| 24 | Shanghai Spheres | Michael Tait | 2018 | non-academic | Shanghai Spheres |

**Table 7: Overview of the 24 non-academic case studies used for the ideation phase and concept models.**

## Appendix Z FABRICATION TECHNIQUES

In the ideation phase and development of the concept models, an exploration of 4 academic and 6 non-academic case studies significantly influenced the fabrication methods of the prototype. Table 8 provides an overview of all these case studies.

| 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 |

**Table 8: Overview of the 4 academic and 6 non-academic sample case studies used as inspiration for fabrication of the prototype.**