Understanding and Designing Data Experiences for Environmental Awareness in the Context of Wellbeing for the Quantified Workplace.

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March 2024

Thesis submitted for Doctor of Philosophy

Chapters Word Total: 98.663

Abstract

This PhD Thesis responds to the timely topic of the quantification of the workplace and the emerging wellbeing challenges of inhabiting sensory-rich workplaces prior, during and post COVID-19. This PhD Thesis adresses relevant research gaps within Human Computer Interaction (HCI) and Human - Building-Interaction (HBI) research through a design-led and mixed-methods methodological approach; responding to the topic in a three-fold way. First, it unpacks the experiences of the occupants of a quantified building while working in the office, at home and in hybrid context; discussing their experiences of data collection and use in these contexts. Second, it maps the emerging wellbeing challenges in the shared, domestic and hybrid workplace; and discusses how these might inform data use for supporting wellbeing in the buildings for work. Third, it addresses the research challenges through designing, deploying, and evaluating a data awareness interface as a means to support wellbeing in the workplace; investigating the experience of air quality data and its representation through a physical customizable display. Key findings of this PhD work relate with how physical aspects influence the perception of privacy in the quantified workplace and may support or inhibit dimensions of wellbeing; emphasizing on the importance of surfacing data in the buildings for awareness and the potentials of engaging with a physical and material design approach for displaying building data to the occupants. An important finding also includes the association between perceived wellbeing and specific environmental aspects; whereby air quality was found to be an important latent aspect for wellbeing while working from home. Finally, an interesting finding includes novel dimensions for biophilic design as key components for designing for wellbeing in the workplace; shaping design directions for physical feedback for environmental data awareness that engages with biomimicry. Responding to the above key findings through materializing and evaluating ActuAir, an air quality data awareness interface, this PhD work opens the design space for customizable soft robotics for physicalizing climatic data in the buildings for work. Key contributions of this PhD Thesis to the field of HBI research include empirical knowledge on the human experience of data collection in the shared and domestic workplace and its use in the buildings for wellbeing purposes; design recommendations for the human-centered design of data-rich workplaces; and design implications for architecture-as-display for environmental feedback in the context of workplace wellbeing.

Acknowledgements

I want to thank different people for different reasons that all contributed to my PhD journey. First and foremost, my family. My father for being a source of inspiration for becoming an academic and studying computer science; and for encouraging me to take calculated career risks and persist with my goals. My mother, that worked hard to support (and shape) my academic excellence in younger age. My partner Remco, who, being in the same PhD boat with me, shared the difficulties of this journey and complemented me with his knowledge, skills, eagerness to help and work as a team. I am grateful for our son Leon arriving shortly after I concluded my data collection, introducing me to the most amazing learning experience – being a parent. And I thank him for being a (relatively) easy going baby and toddler, that helped me go through the final stages of this PhD project.

Besides my family, I want to thank my supervisors, colleagues and friends. Especially, I want to thank my main supervisor Dave, the person that encouraged me starting this PhD and helped funding my research work. He has uniquely supported me in a way that made me feel inspired, motivated, trusted, calm and confident. I also thank Abi for being very supportive with my pregnancy and Leon's arrival, and with me continuing in postdoctoral research while balancing family life. Also Vasilis, for first introducing me to Open Lab, for being genuinely interested in my work and progression, and for helping me grow in the field through critical conversations. Finally, I thank the many colleagues in Open Lab and friends that kindly contributed to my research as participants, through supporting me with making software/hardware, or through sharing valuable ideas about my research.

Last but not least, I want to thank my brother, and my old and new dear friends who have been a great emotional support during the past years; during the different stages of my PhD, the lockdown, my pregnancy and my new life as mom. Thank you all for helping me grow academically but also intellectually and emotionally through this PhD.

This work was partially funded by the EPSRC (EP/M023001/1).

Collaborative Work Acknowledgement

All written work in this Thesis is my work. For published works arising from Thesis materials, supervisors have contributed some editing (see next page). The following researchers have contributed to specific aspects of this work:

Thesis Chapter 5: Remco Benthem de Grave, Ridita Ali, and Jan Smeddinck co-lead and helped in producing the quantitative analysis section. They assisted in co-authoring the relevant section.

Thesis Chapter 8: Jan Kučera helped with the technical implementation of ActuAir; developed the software for ActuAir and advised on the hardware. Ishwarya Suresh co-designed and co-facilitated Study 02.

List of Publications & Academic Engagements

Relevant Publications

Eleni Margariti, Caroline Claisse, Sara Nabil, Ben Bridgens, Abigail C Durrant, and David Kirk. 2024. Human Building Interaction and Design for Climate Change. In Companion Publication of the 2024 ACM Designing Interactive Systems Conference (DIS '24 Companion). Association for Computing Machinery, New York, NY, USA, 462–466. https://doi.org/10.1145/3656156.3658386 **(Thesis Chapter 9)**

Eleni Margariti, Vasilis Vlachokyriakos, Abigail C Durrant, and David Kirk. 2024. Evaluating ActuAir: Building Occupants' Experiences of a Shape Changing Air Quality Display. In Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24), May 11–16, 2024, Honolulu, HI, USA. ACM, New York, NY, USA, 21 pages. https://doi.org/10.1145/ 3613904.3642396 **(Thesis Chapter 8)**

Eleni Margariti, Vasilis Vlachokyriakos, and David Kirk. 2023. Understanding occupants' experiences in quantified buildings: results from a series of exploratory studies. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, 1–15. https://doi.org/10.1145/3544548.3581256 **(Thesis Chapter 4)**

Eleni Kalliopi Margariti, Ridita Ali, Remco Benthem de Grave, David Verweij, Jan Smeddinck, and David Kirk. 2021. Understanding the Experiences of Remote Workers: Opportunities for Ambient Workspaces at Home. Frontiers in Computer Science 3: 673585. https://doi.org/10.3389/fcomp.2021.673585 **(Thesis Chapter 5)**

Other Publications

Benthem de Grave R, Bull C, Monjardino de Souza Monteiro D, Margariti E, McMurchy G, Hutchinson J, Smeddinck J. 2024. Smartphone Apps for Food Purchase Choices: Scoping Review of Designs, Opportunities, and Challenges. J Med Internet Res 2024; DOI: 10.2196/45904.

Eleni Margariti, Sean Rintel, Brendan Murphy, and Abigail Sellen. 2022. Automated mapping of competitive and collaborative overlapping talk in video meetings. In CHI Conference on Human Factors in Computing Systems Extended Abstracts, 1–8. https://doi.org/10.1145/3491101.3519612

Workshop Engagements

Eleni Margariti, Vasilis Vlachokyriakos, Abigail Durrant, David Kirk. 2024. Investigating new models of consent for human-centred AI in the built environment in the context of health and wellbeing. Submitted as a position paper to workshops "HabiTech" and "Designing (with) AI for Wellbeing" in CHI Conference on Human Factors in Computing Systems (CHI '24), May 11–16, 2024, Honolulu, HI, USA. **(based on Thesis Chapter 4)**

Eleni Margariti, David Kirk. 2022. ActuAir: Exploring Physicalizations of Air Quality at the Workplace. In CHI Conference on Human Factors in Computing Systems Workshops & Symposia, April 29–May 05, 2022, New Orleans, LA, USA. ACM, New York, NY, USA, 5 pages. (Presentation Paper). https://www.softrobotics.io/chi22 **(based on Thesis Chapter 7)**

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SECTION A. FRAMING THE RESEARCH PROBLEM SPACE

INTRODUCTION, BACKGROUND, METHODOLOGY

Chapter 1. Introduction

1.1 Background and Motivations

This PhD project began and evolved around a building; a so-called 'smart[1]' office building [44,332]. A lived-in "quantified" building [247] that collects an immense amount of data – an average of 1000 data points[2] – accessible but rather underutilized. Urban Sciences Building (USB) - widely known as a smart building - is a sensory-rich five-story office & research facility building in Newcastle Upon Tyne, UK, with open access to collected data through an API[3] (see Figure 1). USB is a unique case of a smart building as a living-lab, providing excellent research opportunities for Human Computer Interaction (HCI) [271], and specifically Human Building Interaction (HBI) [142,143,169,331,332] and Design research [129,425]. Opposed to other smart office buildings such as The Edge[4], Deloitte, Amsterdam [171], USB is highly accessible – both physically and digitally; and opposed to other smart living labs – see the PEARL[5] [8] – it is a real lived-in building, not a lab that has been created to imitate one. Treating this smart building as a 'quantified' living lab [8] and as a paradigm for understanding the timely phenomenon of increasingly inhabiting sensory-rich buildings [331,332], this PhD contributes to the limited works addressing the building occupants' experiences in such lived-in sensory rich environments; unpacking how the quantification *of* and *in* the built environment is experienced by its occupants in the context of the workplace [222], and envisioning data-use futures through Design Research.

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[1] Defining what a smart building is – see Chapter 2.1.1.

[2] The building has roughly 1000 sensors (entities); whose readings (feeds) are obtained real time at irregular intervals – whenever a reading change is detected. Timeseries data are kept accessible in the web for 24hours by default, but can be requested via the API through providing a specific date range. Data is made accessible through a WebGL interface https://3d.usb.urbanobservatory.ac.uk/ and directly via the API https://api.usb.urbanobservatory.ac.uk/#/definitions/Timeseries

[3] Data is made accessible through a WebGL interface https://3d.usb.urbanobservatory.ac.uk/ and directly via the API https://api.usb.urbanobservatory.ac.uk/#/definitions/Timeseries . The Web Interface shows a 3D model of the building and the data points in each floor. Clicking on these points reveals a list of the real time sensory readings and their 24h timeseries.

[4] https://www.bloomberg.com/features/2015-the-edge-the-worlds-greenest-building/

[5] https://www.pearl.place/

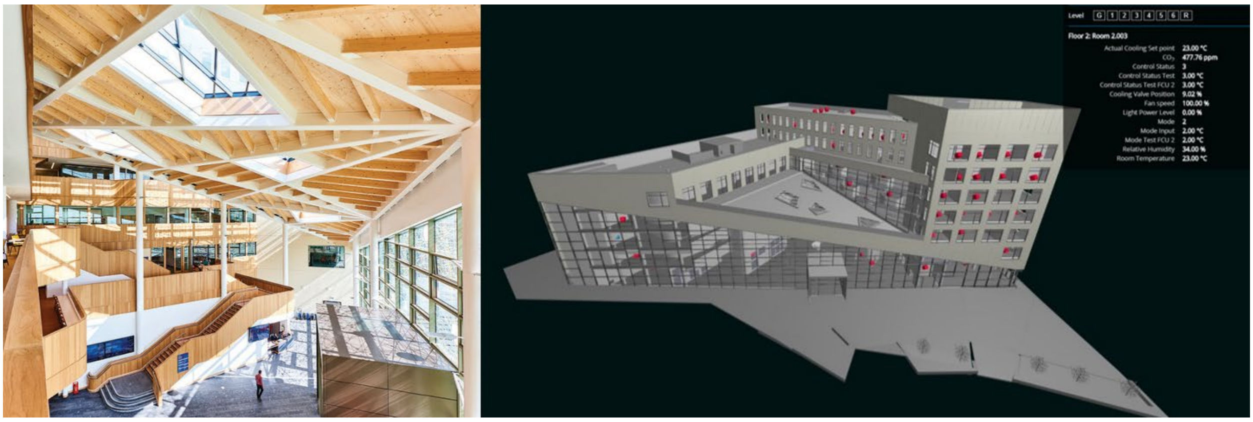

Figure 1: On the left, the reception of Urban Sciences Building (USB), UK; on the right, the open API with the sensory readings from all building's floors provided through a Web interface.

This PhD also took place within a period of rapid changes in the workplace in UK & EU, which both impacted and informed the content of this Thesis and the studies and approach taken. COVID-19 shifted the focus from office buildings to home office, from the shared to remote, and from office spaces to the domestic office. COVID-19 gave a huge boost to preexisting wellbeing concerns[6] in the buildings for work – referring both to the domestic and shared workplace - particularly related to environmental wellbeing [308,350] and air quality [221] at shared and home offices; but also with regards to social wellbeing [18] and the lack of physical activity [114] when working from home. COVID-19 boosted the use of varied environmental monitoring and self-tracking technologies for supporting the health and wellbeing of remote workers [127,227]; further boosting the quantification *of* – or rather *in* – the workplace [222]. Examples include the widespread use of Fitbit and other commodity bands for physical activity monitoring[7] in the workplace; workplace mental wellbeing and group wellbeing apps[8]; and portable air quality monitors[9] , heavily used at home office or at the shared workplace. COVID-19 gave rise to a new era for the quantified workplace under the term 'hybrid workplace' [256], used to describe the complex reality of working from home and the office. There are prominent research gaps mapping the diverse opportunities and challenges for wellbeing in the context, and with regards to designing for wellbeing in the hybrid workplace; making this works' contribution relevant and timely.

Summarizing, this PhD work positions itself between these two major tensions of our times: on the one hand, the instrumentation and quantification of the built environment and the work-life in it; on the other hand, the challenges around wellbeing in the shared and domestic workplace and the discussions on how data collection and data use in-place can address them. These two tensions form the main Topic Axes (see Figure 2). Within this landscape, this work tries to map and unpack experiences of the building occupants in the shared and domestic quantified workplace; and create a design agenda to address in-place data use for wellbeing in that

[6] See research on workplace wellbeing and contemporary issues – Chapter 2.2.3.
[7] https://www.teem.com/blog/workplace-wellness-apps
[8] see https://yourwellspace.com/ or http://ourbalance.com/
[9] https://www.ikea.com/gb/en/p/vindriktning-air-quality-sensor-80515910/ or https://luftio.cz/

context. This could be framed as the key Research Challenge of this PhD work; to map the experiences of the building occupants in the shared quantified workplace, and design interventions that address in-place data use for wellbeing.

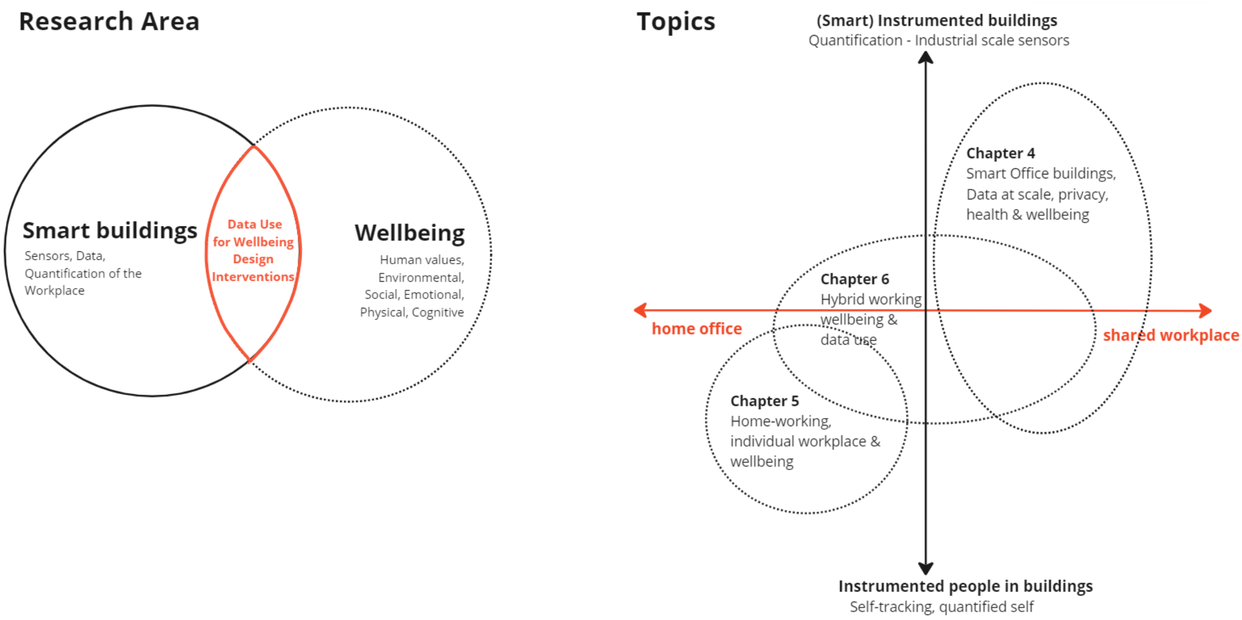

Figure 2: Research Area (left) and Topics addressed by the different Chapters (right)

The key motivation behind this research journey originates from the idea of bringing my academic background and my professional career together. This PhD could be seen as an attempt to 'bridge' my studies and professional practice in architectural design, with my recent career as a User Experience (UX)/ User Interface (UI) designer and digital consultant. In my last job as a digital transformation analyst, I similarly focused on the workplace; from the point of improving internal processes using interactive technologies. Part of the Information Technology (IT) Digitalization & Innovation (D&I) team, we were a driving force in the digital transformation of the company, exposing employees of other departments to how interactive technologies can change their daily workflows through making prototypes. These served as a lens to the future, helping the rest of the company envision the change they want to have in their own core business, workflow, processes, and training. The same creative lens and applied design research approach has also been employed throughout my PhD; combined with my deep interest in designing and innovating for the workplace. The same interest also led me to take up an internship with Microsoft Research (Future of Work group), to investigate the internal transition into hybrid practices; focusing on assessing inclusion from pre-recorded meetings' data[10] [217].

Instead of the organizational aspects of the workplace, this PhD focuses on the buildings we inhabit and work in, treating spaces, places and data experiences in them as the driving force

[10] https://www.microsoft.com/en-us/research/project/blended-reality-encounters-and-workflows/

for innovation in the workplace. The design of smart places for work can be reframed and re-thought with an emphasis of how these buildings are experienced by their occupants; bridging the top-down world of the architects & engineers and the bottom-up one of the people that use and inhabit such buildings. Leading from this, my primary research interest lies in developing technologies that can enhance the human experience of data in the workplace buildings with a view to support their wellbeing. I will further provide an overview of the current research landscape and pressing research challenges herein; and how this PhD work positions itself in it and addresses some of them. Referring to the main research challenge and research topic axes as described above (see Figure 1); the next section provides a more in-depth overview of the research landscape, addressing the key literature that has shaped the most recent research developments in the fields of Human Computer Interaction (HCI) and Human Building Interaction (HBI) research fields.

1.2 Positioning this PhD: Research Landscape and Pressing Challenges

Contemporary buildings have become arenas where extensive data collection takes place. Under the so-called 'smart buildings' agenda [44,231], more and more office and domestic environments[11] are built to be permanently sensory-equipped and monitoring, collecting and processing a massive amount of data sets [332]; e.g. environmental, post-occupancy, operational data. The phenomenon of lived-in quantification [8,332] emerges as the result of the constantly increasing tendency to build and inhabit sensory-rich buildings. Another dimension of lived-in quantification in the buildings relates with the quantified-self movement [63,97,98]; as the building occupants become 'instrumented' themselves [8,210] wearing tracking devices such as fitness bands and sharing their data to other services and technologies within smart buildings[12]. The phenomenon of lived-in quantification of and in the buildings [8,332] presents a diverse research case with unique characteristics. As data tracking is spatialized, contextualized, and, opposed to self-tracking [210,247](or the so-called quantified-self movement) often involuntary, quantified smart buildings compose a unique and highly complex emerging research context; which is of high interest for HBI [142,143] research field.

Human Building Interaction (HBI) research primarily focuses on research in the human experience of data in sensory-rich buildings, and the human-centred design of "quantified" or smart buildings [142,143]. In other words, HBI research is the study of how people interact with digitally augmented buildings- including sensors and the data they collect and/or digital technologies embedded in the buildings such as media facades. Quantified "smart" buildings can provide the ground data infrastructure for HBI research on improving lived-in spaces and the experiences in them. To serve the above research purpose, some smart buildings are intentionally built as a real place and a research infrastructure at the same time – e.g. London

[11] See for instance Newcastle future homes, https://newcastlehelix.com/residential
[12] e.g. connecting Fitbit to Amazon Alexa

PEARL Living Labs[13]. Still, there are plenty of examples where the line between research infrastructure and lived in smart building is hard to be drawn; which has direct implications on the ethical use of data for research in that context. In some cases, what differentiates a living lab from a lived-in smart building is the data access and ownership, the access to the space and infrastructure, and the focus and scope of a potential research agenda for the place [8]. Urban Sciences Building (USB), the office building which is the focus of this PhD work is a lived-in office, study and research building part of Newcastle University, UK; is developed with the potential of being a research facility – albeit not explicitly stating so. Being highly monitored, the building provides the ground data infrastructure for HBI research and data use applications to take place; while operating as an office/university building. The availability of the open datasets and access to a lived-in quantified workplace such as USB creates great opportunities for HBI research; together with ethical responsibility on the use of collected data. Broader present challenges of lived-in quantified spaces relate with data sharing -i.e. what and how data is shared between individuals, and between individuals and organizations - data visibility – i.e. what data is the user able to experience in the building and how - data use – i.e. applications for wellbeing and collective life - data control, and ultimately, the privacy of the building occupants [26,133]. Arguably, the reality of lived-in smart office buildings has many unresolved complexities with regards to their users' experiences, such as the feeling of control on their environments [124,343], and perceived and actual privacy [5,90,133,392,414,420]; whereby further research is meaningful. This PhD contributes in these challenges through investigating the building occupants' experiences (following exploratory, Mixed and Design Research methods), mapping existing concerns and open challenges with regards to the intensified data collection in the buildings for work, with a view of *Designing for Human-Centred Smart Workplaces* [215]. Key findings address aspects of physical scale and scale of data in forming perceptions of privacy; and the importance of creating infrastructure to experience data in the building, pointing towards physical, tangible and ambient interfaces for data awareness [215].

Moreover, research on wellbeing in quantified smart buildings remains a rapidly evolving field [221,308,350]. The focus on the workplace buildings and data for wellbeing is on the hotspot; primarily due to COVID-19 pandemic and the challenges it imposed [227,356]. The COVID-19 pandemic was an accelerating force in the early 2020s for transformations in the workplace such as the rise of remote working, the rise in use of self-tracking technologies for wellbeing monitoring [228] – e.g. fitness bands – and the increased interest in monitoring air quality in the workspaces – see Hilo [83,422]. Research on air quality awareness in office spaces was until recently limited - with very recent works addressing this aspect in the domestic or hybrid workplace. Ambient and physical climatic feedback have great potential to support the wellbeing of remote and shared workers [216]; but there is a lack of background and understanding of the domestic workplace in terms of the occupants' experiences and wellbeing challenges, and the complexities around data use and data sharing in that context.

[13] https://www.pearl.place/

Some of these research gaps are addressed in this PhD work through empirical findings; including establishing correlations between perceived wellbeing and air quality; the importance of feedback when working in isolation; and novel aspects of biophilic and biomimetic design [180,424] in the hybrid workplace, linking nature with social and physical wellbeing.

Within this research landscape and challenges; this PhD employs Design Research to address some of the unresolved complexities. The above empirical findings are further translated into design directions for physical interfaces for climatic data awareness in the context of the human centered workplace. In this PhD project, Design Research on human-centered smart buildings addresses aspects of wellbeing through rethinking the physical, tangible and material dimensions of data in-place. Relevant research on wellbeing has informed contemporary building design practice– see WELL[14] and PROWELL[15]; as well as the development of diverse technologies to communicate and collectively manage data for wellbeing in the shared and remote workplace. Still these two dimensions – i.e. the physical design and data use - do not meet as much as they could. This PhD work contributes towards this direction, through defining a physical and material design agenda for human centered quantified workplaces for wellbeing; and designing, deploying and evaluating ActuAir, a physical intervention that addresses this agenda. ActuAir is a large customizable shape and color changing display for surfacing air quality data – and broader climatic data – in place. Design contributions of this PhD work relate with both ActuAir's conceptualization and materialization, as well as with the empirical knowledge on how the building occupant's experienced ActuAir. Contributions include the findings on the experience around this shape-changing architecture-as-display in the context of communicating climatic (air quality) data and supporting environmental wellbeing.

The underpinning research field that this PhD is contributing to is Human Building Interaction (HBI)[142,143,209,317] research. HBI is concerned with the human-centered dimension of smart buildings' design, focusing primarily on human experiences, values and needs of the occupants of smart environments [142]. Following the work of Shen et. al. [1], Nembrini and Lalanne [142], and Alavi et al [9], HBI research focuses on how occupants interact with buildings - *the study of the interface between the occupants and the building's physical space and the objects within it* [337]- to provide a foundation to inform and direct the development of human-centered [122] (and not merely user-centered)[16] smart buildings. In addition, Adaptive Architecture research [169,189,246,329,331,374,404] focuses on the power of the physical and material dimensions of architecture as an interface, following an embodied and

[14] https://www.wellcertified.com/
[15] https://www.innovativeworkplaceinstitute.org/workplace-wellbeing-prowell.php
[16] By focusing on usability, the HCI literature too often overlooks the social context of use. Bjorn-Andersen (1988) criticized the narrow definition of user-centered computing in human computer interaction (HCI) in the literature, with the words: "it is essential that we see our field of investigation in a broader context. A 'human' is much more than eye and finger movements". So how do we design for human-centeredness? Gill (1991) defines human-centeredness as "a new technological tradition which places human need, skill, creativity and potentiality at the center of the activities of technological systems."

enacted approach to interaction [169]. HBI research ultimately shifts the focus from ‘smart buildings’ and ‘users’, to a wider smart agenda towards achieving sustainability, meaningful usage, and wellbeing in the buildings together with their occupants [142]. Summarizing the key empirical and design research contributions of this PhD to the field of HBI research are empirical findings on the experiences of the building occupants of quantified workplaces; the framing of a physical design agenda that addresses human-centered workplaces and data use for wellbeing in that context; and based on this, the design and evaluation of a physical customizable air quality data display in-place, with the view on producing generalized knowledge on the applicability and scalability of this agenda.

1.3 Research Questions, Aims and Objectives

Responding to the above research gaps and challenges, the following Research Aims, Objectives and Questions were articulated for the doctoral project. There is an inherent dualism in the way this PhD responds to the Research Challenge below; referring to empirical research driven by a Mixed Methods approach to collecting and analyzing data, and Design Research, responding through designing and developing interventions and artifacts. This approach of doing both Mixed-Methods and Design Research in attempt to respond to the research challenges above is further analyzed in the Methodology section, but is also mapped in the Research Aims, Objectives and Questions below, as well as in the overall structure of the Thesis.

1.3.1. Research Challenge

My Research Challenge is to map the experiences of the building occupants in the quantified workplace, and design building interventions that address in-place data use for wellbeing.

1.3.2. Research Aims

My Research Aim is to explore how the building occupants experience quantification of and in the workplace (following a mixed methods approach), and design and evaluate interventions that support data experience for wellbeing in the buildings for work (following design research approach).

1.3.3. Research Objectives

My Research Objective is to map experiences of the building occupants in the quantified workplace (office buildings and home office) following exploratory Mixed and Design research methods. Mixed methods include qualitative and quantitative methods to analyze data obtained through focus groups, surveys (online diaries) and commodity wearables. Design Research Methods include co-creation, co-design and design fiction workshops and prototyping artifacts.

Based on the key empirical findings produced from the analysis of data using the above research methods, my objective is to synthesize a design agenda that addresses data use for wellbeing in-place in the context of the quantified workplace.

Utilizing this agenda, my objective is to design, build and evaluate design interventions (following a Design Research methodological approach) to support the human experience of environmental data in the quantified buildings for wellbeing purposes.

1.3.4. Research Questions (RQs)

RQ1: What are the experiences[17] of the building occupants[18] in the quantified[19] workplace[20]?

RQ1 can be further specified:

- How do the building occupants experience working at the quantified shared and home office?
- How do the building occupants experience quantification - i.e. data collection at scale, tracking and self-tracking - in the shared and home office?

RQ2: How can their experiences inform data use for wellbeing in the buildings for work?

RQ2 can be further broken down:

- How do the building occupants experience data collection & use for wellbeing in the buildings for work – i.e. office buildings and home office?
- How can their wellbeing-related experiences inform data use for wellbeing in the shared and home office?

RQ3: What design interventions can support data experience[21] for wellbeing in the quantified buildings for work?

RQ3 can be further broken down to:

- What interventions can be designed to support wellbeing through utilizing data?
- How can design interventions in the buildings for work enhance the building occupants' experience of data to support wellbeing?

With the term 'building occupants' experiences' purposefully being broad, the formulation of the above research questions naturally points towards engaging with an exploratory design-led methodology to respond to them. The term of building occupants' experiences narrowed

[17] Experiences: lived-in experiences in places involving data collection and physical space.
[18] Building Occupants: the residents of a building.
[19] Quantified: referring to quantification; data collection at scale, tracking and self-tracking
[20] Workplace: referring to the home office, the shared workplace (office buildings) and the hybrid working.
[21] Data experience: experience of data in-place

down to addressing specific aspects of this experience through exploratory research – e.g. experiences relevant to data or wellbeing.

It is important to highlight that the research questions were developed through an inductive research approach, not a deductive approach. Being inductive, this research focuses on understanding human experiences, collecting and analyzing data to guide research; instead of doing so top-down through identifying literature gaps. This doesn't mean that the research questions do not address literature gaps (see relevant signposting in Literature Review section), but they did not emerge from the systematic review of literature but through the engagement with the users and their data.

Moreover, RQ1 is a broad research question (could be framed as an 'umbrella' research question), while RQ2 brings the focus on wellbeing and RQ3 on designing interventions. RQ2 and RQ3 do partly map under RQ1, but they also extend beyond its scope and therefore are articulated independently. This also serves to purposefully highlight the associated research gaps in literature and provides clarity with regards to structuring the work of independent research chapters.

Finally, my research focus on wellbeing was also shaped by circumstances such as COVID-19, which intensified the research interest around the domestic and hybrid workplace and for interventions that address air quality in these contexts. Summarising, because of the generative nature this PhD work and the inductive approach followed; there was a conscious effort to synthesize a research question that provides the broader framing (RQ1) and articulate RQ2 and RQ3 independently to highlight the dedicated focus on wellbeing (as further shaped by pressing challenges such as COVID-19) and the complexities of responding to these challenges through design research.

The above RQs are addressed by the Empirical & Design Research chapters; with each chapter responding in a different manner. Chapter 4 revolved around the initial mapping of the broader occupants' views, values and concerns around data collection and use in the office buildings (RQ1), and secondarily to its use for health wellbeing purposes (RQ2). Chapters 5 & 6 primarily revolved around mapping the experiences related to wellbeing in the workplace (RQ2) and secondarily address data collection and use to support wellbeing (RQ2). Chapters 7 & 8 primarily respond to RQ3 through the making and the evaluation of a prototype in place. Briefly, the empirical and design chapters and how they respond to the above RQs is stated below:

Chapter 04. Understanding Occupants' experiences in quantified buildings.

RQ1a: What are the experiences of the building occupants of a quantified (smart) office building?

RQ2a: How do they view data collection and use for health & wellbeing in the building?

Chapter 05. Mapping the experiences of building occupants while working from home.

RQ1b: What are the experiences of building occupants when working from home?

RQ2b: How do they experience data use for wellbeing while working from home?

Chapter 06. Co-designing for wellbeing in the hybrid workplace.

RQ1c: How do building occupants experience the hybrid workplace (working in the office and home office)?

RQ2c: How do they experience use of data for wellbeing in the hybrid workplace?

Chapter 07. Design Research on Physical Displays for Air Quality (AQ) data awareness.

RQ3a: What feedback design can support wellbeing through experiencing data in the buildings?

Chapter 08. Evaluating ActuAir, a shape-changing display for Air Quality (AQ) data awareness in the workplace.

RQ3b: How do the building occupants experience, perceive and interpret this feedback?

1.4 Overview of Methodological Approach and Studies

Methodologically, this PhD aligns with a Pragmatist orientation to research [179]; an approach to doing research through acting [129]. Pragmatism, as a research paradigm, accepts multiple realities that are open to empirical inquiry [179]; rejecting the philosophical dualisms of the Objectivity (i.e. Hypothesis-Driven Research, Post-positivism, Quantitative methods) and Subjectivity (i.e. Exploratory Research, Constructivism, Qualitative methods). This allows the researcher to combine methods that fit in both Post-positivism and Constructivism inquiry [179], using abductive reasoning – hence often guiding the employment of a Mixed Methods approach, combining both Quantitative and Qualitative data analysis. Pragmatism orients the researcher toward solving practical problems in the real world, used as a method of inquiry for the practical-minded [129]. For this reason, it also embraces Design Research [129]. For pragmatists, a sense of Reality is grounded in the environment and can only be encountered through human experience; design research resonates with this philosophical orientation as it can involve knowledge generation through making and interacting with artifacts [129]. Essential in Design Research practice is to consider the introduction of new artefacts as responses to problems and needs in human activities. A new type of artifact is considered as a solution to a perceived problem. The knowledge obtained through making it and observing the human experiences around it can help reframe the initial problem/research question [129].

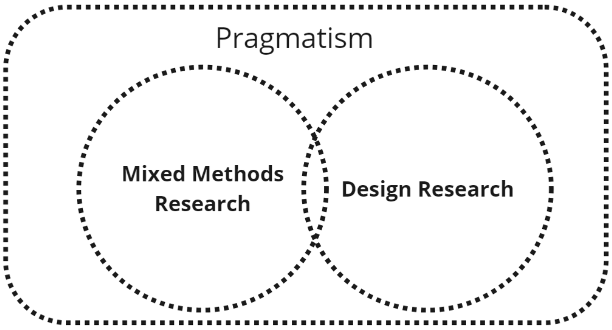

Figure 3: Pragmatism embracing both Mixed Methods Research and Design Research.

Pragmatism allows for flexibility and diversity in the methods chosen to address given study purpose, context and research questions [129]. As a methodological approach, Pragmatism fits with HCI and particularly HBI research, a multidisciplinary action-based research field [142]. As HBI addresses human experiences and relationships with data in the built environment [143]; many related works employ Design Research, building and deploying artifacts in the buildings to explore human-data-environments relationships [331], and Mixed Methods research, utilizing sensing technologies to collect and analyze data on human behavior in the buildings [9]. Similarly with many HBI research projects, this PhD employes both a Mixed Methods approach and Design Research to address the RQs, Aims and Objectives above; which will be further discussed in the Methodology Section (3.1.). Overall, the presentation of the Empirical Findings from this research is organized around two Sections (B & C) (see Figure 4) which both combine elements of Design Research and Mixed Methods (predominantly qualitative) analysis:

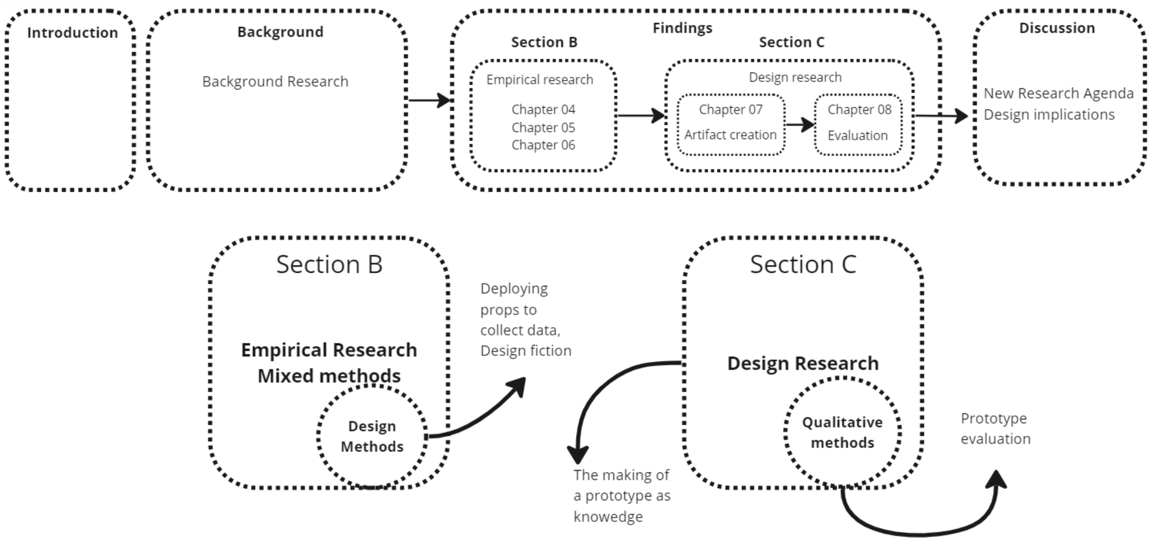

Figure 4: The overall structure of the Thesis (above); and the methods employed in Sections B & C (below).

- *Section B. Understanding People in Place* consists of 3 Chapters. Section B is my account of the empirical research that focuses on understanding people's experiences in the quantified workplace; in the physical context of the office building (Chapter 4), the domestic office (Chapter 5) , and in both (hybrid) (Chapter 6). Mixed Methods have been employed in Chapter 5, as the focus of this chapter was on understanding aspects of the domestic workplace over time. Chapters 4 & 6 focus on analyzing occupants' perceptions and concerns. Qualitative methods (e.g. focus groups) and Design Research employed in these chapters – e.g. Design Fiction (Chapter 4) and Co-Design Workshops (Chapter 6).

- *Section C. Understanding Materiality: Design & Material explorations* consists of 2 chapters: Chapter 7 is the making of ActuAir prototype (Design Research), and Chapter 8 is ActuAir's empirical evaluation in the workplace (Qualitative research facilitated by the prototype's in-situ installation). The focus of this section is on materiality; on building an intervention as a response to past findings and an understanding of the building occupants' perceptions and interpretations of this intervention in the workplace.

Sections B & C naturally differ with regards to the underlying approach driving data collection. In Section B, my interest was studying people in naturalistic context; and therefor I tried to be as little interventionist as possible. This extends to the choice of sensory deployment used in each context; based on factors such as scale (of sensory infrastructure) and acceptability. For example, in Chapter 4 which focuses on the smart building, the already installed industrial sensors and their data output is used in the studies to map participants' views; whereas in Chapter 5 which is about the domestic workplace, commodity wearable sensors were used as they are already widely accepted and used at home and the workplace. It is also important to note that the research focus in these Chapters and associated studies was not on environmental data only; but the broader experience of quantification of and in the workplace; which further justifies the above selections on scale of sensory infrastructure.

It is also important to highlight that Section C does not aim to respond to all findings and design considerations from Section B; but addresses key findings and design considerations as summarized in Chapter 6. The studies described in Chapter 6 were key in terms of identifying key findings through triangulation of research topics and methods (i.e. focusing on both the domestic and shared workplace, to validate findings as emerged in the previous Chapter). However, with this PhD work being generative in nature; each chapter provides its own contributions while opening new opportunities for further research. Following this approach, Section C responds to key findings while framing new opportunities and challenges for design research.

Pragmatism eschews an a-priori determination of all experimental variables to be tested [179]. Under the Pragmatism lens, this PhD was designed as a generative program of work that would organically evolve over time, adapting to unforeseen situations and changing circumstances - such as the move to remote data collection during COVID-19 lockdowns and the varying interests and engagement levels of the participants. In fact, the shift in the workplace imposed by COVID-19 was seen as a research challenge and research opportunity; adapting the research topic area to embrace these unforeseen changes.

Beyond COVID-19, this generative approach of doing research is central in this work; as specific themes and concepts observed in the findings gained importance over time and became a driving aspect over the course of this PhD. The initial broader focus on the experience of quantification of the workplace (Chapter 4) was further narrowed to wellbeing-related experiences and study of the experiences on data collection and use for wellbeing (Chapters 5 & 6). The association of perceived wellbeing with perceived was a key finding in Chapter 5 which then further drove the focus around environmental/climatic wellbeing and data for air quality in the hybrid workplace (Chapter 6) and the design and evaluation of interventions that respond to environmental and air quality data (Chapters 7 & 8). This focus on wellbeing - on data for health and wellbeing, and air quality in particular – was strengthened because of COVID-19 impact on this research.

1.4.1 Studies Overview

Following the methodology overview, below is a short overview of the Methods, the studies and activities that took place in each chapter. The two sections , Section B: Understanding People in Place; and Section C: Understanding Materiality: Design & Material Explorations both provide Empirical findings and Design contributions. The order of the chapters matches the chronological order of all studies and activities that took place throughout the PhD. Below is a more detailed overview of each Chapter and the studies and activities that take place.

1.4.1.1. Section B. Understanding People in Place | Empirical Research Findings addresses the experiences of building occupants of quantification of and in the buildings of work, across the office and the home office. Each of the three (3) chapters addresses a different dimension of quantification – from instrumented buildings to instrumented people – and different spatial contexts: office buildings, the home office, and both. Chapter 04 talks about the experiences of the building occupants of a quantified office building. Chapter 05 discusses wellbeing and data related experiences while working from home, using self-tracking in that context. Chapter 06 discusses experiences in both office and home office contexts with a focus on wellbeing; validating previous findings and solidifying design directions which will be further explored in Chapter 7.

Chapter 4. Understanding Occupants' Experiences in Quantified Buildings unpacks the occupants' experiences of a quantified building, through a series of 4 exploratory workshops during January and April 2020. Participants projectively explored perspectives of data collection and use in the built environment, highlighting underlying concerns, ethical considerations, values, and attitudes towards quantified office buildings. The aim and outcome of the workshops was to formulate a 'set of user sensitivities' to guide the design and development of future design interventions and research agendas in that space. The workshops employed a range of qualitative research methods such as Focus group discussions, Design Fiction and Story Telling activities. Each workshop contributed towards creating a design agenda for human-centered quantified buildings through a employing a different angle and methods. Workshop 1 is a shared focus group, addressing data collection and use in a quantified building and the views and perspectives of the building occupants. Workshop 2 is a remote focus group, exploring data temporality and the materialization of data over time in the built environment, prompting participants to consider the value of accumulated data over time. Workshop 3 is a remote design fiction workshop, enabling participants to envision their own utopian & dystopian scenarios of smart buildings through story telling. Workshop 4 is an online asynchronous design fiction activity, providing participants with images of interactive data-driven architectures, engaging them in writing stories on how the environment can adapt to the users based on data interactions. The exploratory nature of this work justifies the selection of such broad methods and themes, aiming to understand and widen the design space of quantified environments.

Chapter 5. Mapping the Experiences of Building Occupants' while Working from Home is an exploratory study with 13 participants over a period of 4 weeks; to map physical experiences and the wellbeing while working exclusively from home during June-August 2020. The study involved both qualitative and quantitative measures of occupant experience utilizing sensor wristbands and a custom web application served as a diary for self-reporting mood and aspects of the environment. Based on a Mixed Methods approach (quantitative and qualitative analysis), the study addresses wellbeing challenges of the domestic workplace, establishes correlations between mood and physical aspects, and discusses the impact of feedback on the behavior of remote workers. Insights from these observations are then used to inform a future design agenda for ambient technologies that supports the wellbeing in the domestic workplace (with a view to hybrid); addressing the design opportunities for ambient interventions in the domestic workplace.

Chapter 6. Co-Designing for wellbeing in the hybrid workplace consists of 2 workshops, both framed around wellbeing in the hybrid (office and home-office) workplace; engaging 13 participants in total during May 2021. Workshop 1 is a remote focus group with 7 participants (from the same shared workplace). Guided by PROWELL model wellbeing categories, participants discussed wellbeing challenges and opportunities in the shared and home office; and reflected how data collection and use in the buildings can support their wellbeing. Workshop 2 is a remote co-design activity with 6 participants and a purpose-made card deck; exploring design ideas around data collection and use for wellbeing in the workplace, with an emphasis on the physical, tangible and spatial dimension of imagined interventions. Using the purpose-made card deck; participants were encouraged to combine Wellbeing[22], Sensor, Spaces and Action/Interaction cards, and envision fictional technologies to support wellbeing in the workplace.

[22] PROWELL model of workplace wellbeing assessment was used as a basis to form wellbeing themes categories.

1.4.1.2. Section C. Understanding Materiality: Design and Material Explorations | Design Research and Empirical Findings is predominantly Design-Research driven and consists of 2 chapters. Chapter 7 presents the design and making of artifacts for physicalizing broadly environmental, and more specifically air quality data, through images and illustrations; Chapter 8 presents empirical findings from the evaluation studies of the final prototype (ActuAir).

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Chapter 7. Design Research on Physical Displays for Air Quality Data Awareness describes the design and material experimentation and the making of the final ActuAir prototype from October 2021 to June 2022; as a response to the findings of the previous 3 chapters. In Chapter 7, I present the design process of a novel large, configurable, shape and color changing display for communicating AQ data to occupants of a smart (workplace) building; a modular customizable room divider heavily inspired by biomimetic concepts, which displays AQ data through inflation and LED animations. Chapter 7 has an "activities' section, consisting of 4 sub-sections, presenting the design work progress in a chronological order. Material is presented heavily utilizing images to document the design experiments with materials and electronics; following a portfolio[23] approach. The reporting of all steps shows the importance of failed experiments in the learning process; with each learning framed under "opportunities and challenges". These are the small design contributions of this section, reported across all sub-sections. In further detail, Sub-section 7.4.1. concerns initial design research including concept design and 2D & 3D design work of artifacts. It starts with a brief mapping of biomimetic design patterns (including shape & color change) in architectural and interior design; addressing colors, materials and design forms. It then describes the 2D & 3D design process of artifacts; accompanied with the decision of using or abandoning specific materials and color & shape change patterns. It ends with the development of animated 3D examples of the future artifacts; used as validation tool for progressing to the next stage of physical prototyping. Sub-section 7.4.2. concerns the physical prototyping; the process of making the artifacts, illustrating the failed and successful design experiments of form-finding, material combinations, user interaction and data interactivity; accompanied with the development of different hardware to control it. It explores two distinct actuation systems: folding/unfolding using felt fabric and SMA wires, and inflation/deflation using silicone rubber and air pumps; and color change across both systems. At the end of this unit, decisions are made on which of these two systems is promising and can be further explored. Sub-section 7.4.3 described further material research on the selected actuation system (pneumatics); the attempts to combine color change with inflation, and the introduction of LEDs to overcome problems. Sub-section 7.4.4 describes the making of the final prototype together with the development of hardware and software to control it. The discussion concludes with a summary of the key takeaways – i.e. knowledge obtained through successes and failures, and avenues for further research.

[23] Portfolio approach is an approach of showcasing the design research process and the prototypes documented primarily through the use of images and figure captions.

Chapter 8. Design Evaluation: Understanding Building Occupants interactions with ActuAir air quality display. Chapter 8 presents the evaluation of ActuAir prototype through 3 exploratory studies facilitated by the prototype's installation in-situ; during June-August 2022 with 21 participants, all occupants of the same smart building and shared office space. Study 1 is a series of 3 hybrid design criteria evaluation workshops with 12 experts, discussing their perception and experience of the prototype's success in displaying air quality data; addressing aspects of physical feedback, materiality and design, and data configurations. Study 2 is a shared co-creation workshop with five participants focused on the experience and interpretation of biomimetic feedback. The participants were exposed to the installed prototype and to different pre-videorecorded feedback configurations; illustrating different physical arrangements and light and inflation sequences achieved with the prototype, all inspired by biomimetic metaphors. They were asked to discuss their understanding of the different configurations, and finally, envision how they would configure and use the prototype in the workplace. Study 3 includes interviews and a survey with 7 participants following a two-week deployment of the prototype in situ within the workplace. The participants were asked to reflect on how they experience the prototype in-place; and what do they make out of it. Collected data from all studies were qualitatively analyzed; providing insights on how the building occupants experience and interpret the display; deliberately both in absence of, and in knowledge of, what data it represents. The results of these studies unpack how the building occupants perceive, interpret, and experience the display; their sense-making with regards to AQ data; and what their expectations and aspirations are in terms of configuring and using the display within the workplace.

1.4.2. Thesis Structure

Below a high-level diagram with the structure of this PhD Thesis (Sections & Chapters) (Figure 5). Section A consists of the chapters 1-Introduction, 2-Literature Review (or Background) and 3-Methodology. Section B consists of Empirical Chapters 4,5 and 6. As illustrated in the diagram below, Chapter 6 is a triangulation chapter in the sense it addresses the shared (Chapter 4) and domestic (Chapter 5) workplace together. Chapter 6 summarizes key findings and introduces the next design research section, Section C. Section C starts with Chapter 7, which is the documentation of all the design research and material exploration towards making the final prototype. Chapter 8 is the empirical evaluation of his prototype. Section D consists of Chapter 9, which is the discussion of the Thesis; summarizing the key points of all discussions in each chapter, synthesizing those into a unified framework/agenda and framing next steps for research.

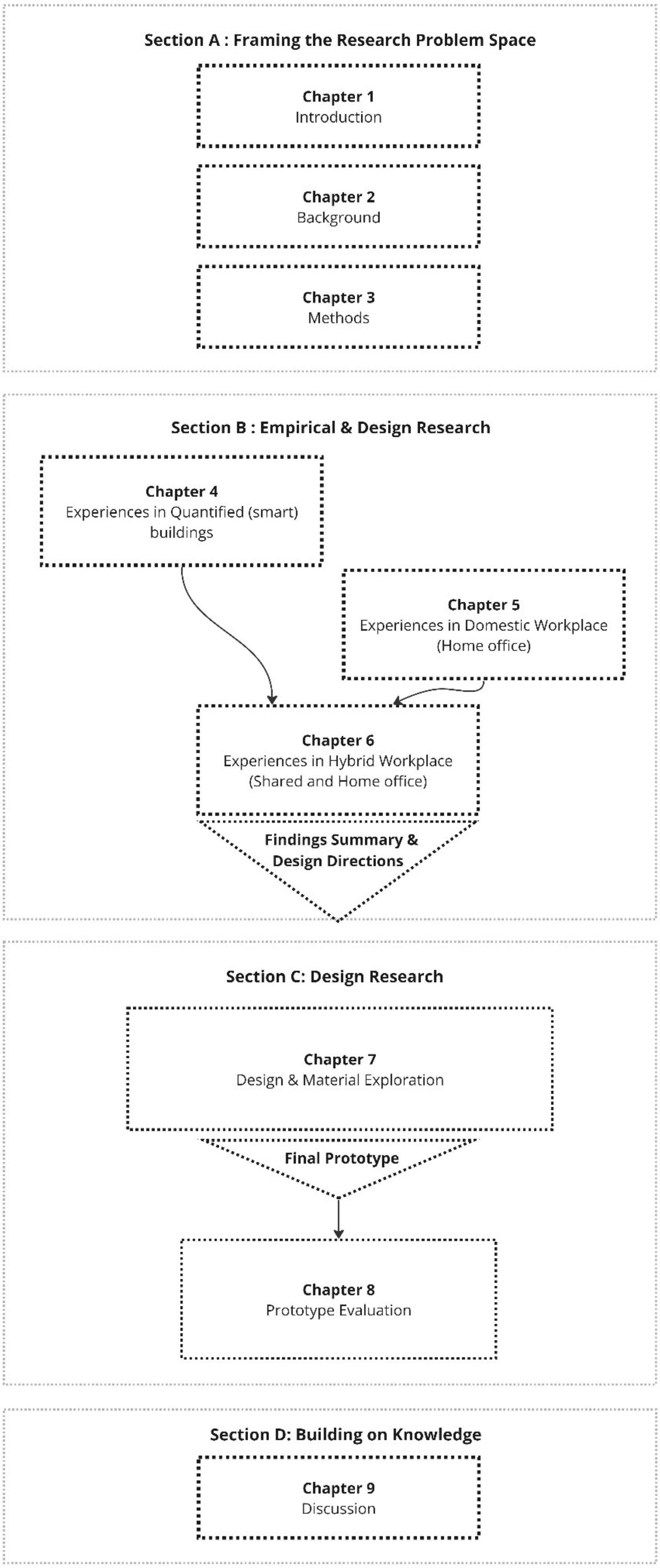
Section A : Framing the Research Problem Space
Chapter 1
Introduction
Chapter 2
Background
Chapter 3
Methods
Section B : Empirical & Design Research
Chapter 4
Experiences in Quantified (smart) buildings
Chapter 5
Experiences in Domestic Workplace (Home office)
Chapter 6
Experiences in Hybrid Workplace (Shared and Home office)
Findings Summary & Design Directions
Section C: Design Research
Chapter 7
Design & Material Exploration
Final Prototype
Chapter 8
Prototype Evaluation
Section D: Building on Knowledge
Chapter 9
Discussion

Figure 5: Thesis Structure. Chapter 6 serves as a data-triangulation chapter as it addresses both the shared and the domestic workplace, validating insights from the previous 2 chapters.

1.5. Contributions

In this PhD Thesis, I make the following empirical and design contributions to the fields of Human-Computer-Interaction (HCI) and Human-Building-Interaction (HBI) research [143,209]. Broadly, these relate to findings on how people experience data in the quantified workplace; and more specifically to how people experience data in the shared, domestic and hybrid workplace. Moreover, findings on aspects of wellbeing in these contexts particularly point to the importance of air quality and have direct design implications for data use in the quantified workplace. Finally, it provides with practical knowledge on designing and building physical customizable awareness displays for air quality data (and broadly climate data) experience as way to support wellbeing in the workplace; and the building occupants' perception and interpretation of data form design implications for the future design of climatic displays in the buildings. The contributions of each of the empirical chapters are further illustrated below.

In Chapter 4, the studies and findings contribute to the limited number of studies in lived-in smart office buildings that focus on their occupants' experiences. Key contributions are the empirical account of the building occupant's experiences and the synthesis of a design agenda for the human-centered design of smart office buildings. Key findings discuss physical scale and scale of data collection in relation to perceived privacy. Moreover, findings address the building occupants' confusions with regards to what data is personal and their perceived underutilization of data for the occupants' benefit and use, emphasizing on the importance of surfacing data in the buildings. Finally, the conflicting views over AI control of data use for health and wellbeing in the buildings are presented reflecting relevant HCI/Ubicomp research.

In Chapter 5, findings contribute to pressing research gaps on technologies to support wellbeing in the domestic workplace. The key contributions are twofold: a) A qualitatively and quantitatively informed understanding of the experiences of home-workers and their wellbeing while working from home; and b) a synthesis of a design agenda for ambient technology that supports wellbeing in this context. Key findings include correlations between self-reported wellbeing (mood) and environmental aspects – e.g. air quality -and dimensions of physical feedback for environmental and bodily awareness.

Chapter 6 reports on the building occupants' experiences around wellbeing and discusses their views on data use for wellbeing in the hybrid workplace. Similarly to the above chapters, it shapes a design agenda to drive interventions in that space. Key findings include the perception of control over the environment being a key aspect to support perceived wellbeing; and the relationships between biophilia, social connectedness and physical activity. Chapter 6 contributes with the framing of a design agenda for data use around biomimetic/biophilic design that addresses ambient and physical feedback for wellbeing. As Chapter 6 discusses both the shared and the domestic workplace, it serves as a triangulation chapter; validating key findings from the above three chapters and synthesizing all design considerations into one design directions summary, that will be further explored through Design Research in Chapters 7 & 8.

Chapter 7 responds to findings from the previous chapters through Design Research; designing an environmental data awareness interface (ActuAir). ActuAir is a customizable room divider that physicalizes air quality data in the workplace. Core contributions being the hands-on knowledge on working with specific materials for soft robotics; and future avenues for color & shape changing materials for architecture-as-display for environmental data – particularly air quality data – in the workplace.

Chapter 8 provides empirical contributions on the potential of large-scale soft robotics to provide environmental feedback in-place; through deploying and evaluating ActuAir in situ. Key contributions of the chapter include the analysis of the building occupants' perceptions and interpretations on the display use and its data-driven feedback in-place, considering physical & spatial factors. These findings are synthesized into design implications for the design of soft robotic displays and adaptive architectures for climatic data awareness, addressing architecture-as-display for climatic feedback in the context of workplace wellbeing.

Summarizing the key research contributions of this PhD to the field of HBI research; these are empirical findings on the experiences of the building occupants of the shared and domestic quantified workplace, and, building upon these findings, the Design Implications for the human centered workplace (see sub-section 9.1.2) with particular emphasis on wellbeing (see sub-section 9.1.3.). Based on the design and evaluation of a physical customizable air quality data display in-place, it produces generalized knowledge on the applicability and scalability of a novel design agenda involving physical interfaces for climate awareness. Finally, this Thesis concludes with the framing of a design agenda (a summary and re-synthesis of the design implications presented in empirical chapters) to shape the future of Human Building Interaction research on the human-centered hybrid workplace; addressing ethical data use, climate and wellbeing, and novel interfaces.

Chapter 2. Literature Review

This Background section has three key sections, which foreground different aspects of this PhD work. Section 2.1. is an overview section where key literature on HBI research and works relevant to the workplace are introduced. This section focuses particularly on aspects of data collection and data use as present in the relevant literature. Section 2.2.dives into HBI & wellbeing related literature; relevant to the buildings for work (RQ1, RQ2). It unpacks key themes around wellbeing in the shared and remote workplace, and discusses technologies and approaches used. Section 2.3. is primarily concerned with designing physical feedback (RQ3); providing an overview of the design agenda of Soft Robotics & Actuated materials.

2.1 Framing Human Building Interaction (HBI) research and Smart Buildings

The following sections present key research on Human Building Interaction (HBI) and Adaptive Architecture (AA) literature; foregrounding relevant research on the quantified workplace – including smart buildings - and introducing key works around data collection and use in the lived-in built environment in the context of the workplace.

Rendering technology invisible within the built environment is not a new concern; Weiser's vision for the computer in the 21st Century [385] set a primary direction for the later Ubicomp movement and contemporary IoT environments [207,313]. Contemporaneous examples of the application of such practices are often referred to as smart buildings [44]: buildings that integrate data-collection and processing technologies (IoT, AI) with a view to manage their energy and operation [44]. An example of such buildings is the Edge [171]; an IoT- enabled office building in Amsterdam currently owned by Deloitte. The Edge showcases the benefits of IoT infrastructure and Building Information Modelling (BIM data processing platform) for post-construction building data analysis and use [311,312,372] . The many sensors in the building collect predominantly environmental and occupancy data; processed by BIM for automated energy performance visualization, building usage monitoring and post-processing for energy analysis [171].

Framing what a smart building is, is not that simple; there is great ambiguity to the term (being a market-driven concept) [44,108,171]. Following Buckman et. al [44], a smart building collects and uses data points and AI with a purpose of adapting to the complex needs of their occupants over time [44]. Inherent to this term is the occupant-centric approach of smart buildings [44]; smart buildings should be occupant-based, creating active participants [231,232,313,338] through integrated technologies that provide feedback both towards and from occupants, and methods for user control [215,231,313]. Opposed to a vision of top-down control, of buildings that control their occupants and all aspects of life in them; Buckman et.al [44] open the space for occupant-centered smart buildings. Rogers [313] further emphasizes empowering the building occupants of smart environments to engage in co-shaping the environments they inhabit; an idea that is key in the (more recent) work of Finnigan [231,232].

Human-Building-Interaction (HBI) research focuses on the human-centred dimension of smart buildings [254,337]; unpacking human experiences, values and needs of the occupants of smart environments [9,143,317]. While the "Smart Agenda" for the built environment emphasizes improving efficiency, cost, and sustainability [89,126], utilizing integrated (IoT) technology and interfaces to engage 'users'; HBI addresses people's complex interactions and collective experiences with and within smart buildings [142,143,332], utilizing technology to study human behaviors in smart buildings, and designing technology that aims to foster human-building collaboration [254,317,374] for the purpose of human flourishing in the built environment [332].
By focusing on how occupants interact with buildings - the study of the interface between the occupants and the building's physical space and the objects within it [142,143,337] – HBI research can provide a foundation to inform and direct the development of human-centred [122] (and not merely user-centered)[24] smart buildings [332]. In their paper *Introducing Human building Interaction* [143]; Alavi et al. draft key dimensions of HBI research – spatial, social and physical - and various themes of research, to guide future work in the field (Figure 5).

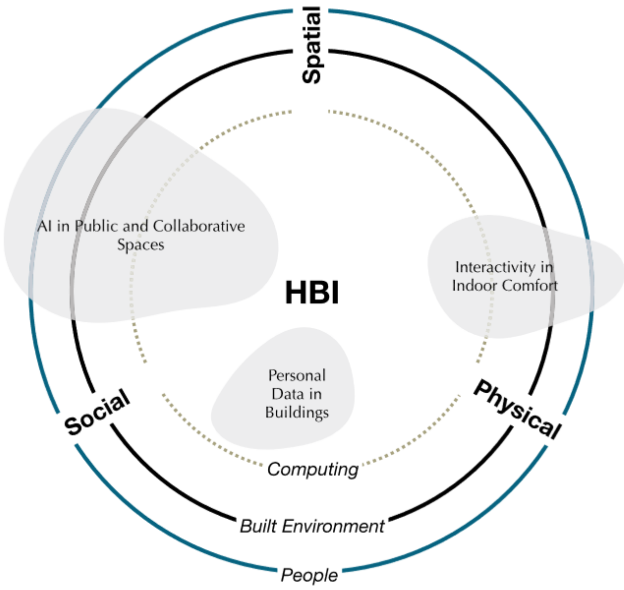

Figure 6: Key dimensions of HBI research by Alavi et al.[145].

Following S. Brand's approach of understanding change in the built environment by focusing on its inhabitants; buildings 'learn' through iterative, slow processes of adaptation and re-appropriation over time [32]. These processes are often visible on different material layers of the buildings; what Brand (and originally Duffy) frames as 'shearing layers of change'; each subject to a different temporal scale of adaptation (see Figure 6)[332]. Along these lines,

[24] By focusing on usability, the HCI literature too often overlooks the social context of use. Bjorn-Andersen (1988) criticized the narrow definition of user-centered computing in human computer interaction (HCI) in the literature, with the words: "it is essential that we see our field of investigation in a broader context. A 'human' is much more than eye and finger movements". So how do we design for human-centeredness? Gill (1991) defines human-centeredness as "a new technological tradition which places human need, skill, creativity and potentiality at the center of the activities of technological systems."

Human Building Interaction (HBI) addresses the temporal dimensions of occupants' interactions with buildings [332]; extending them to include aspects of interactions in contemporary smart buildings. The data layer [374]– inherent to smart buildings – adds another 'shearing layer' and a layer of complexity in human-building interactions; with interactions between buildings and humans becoming much faster [169,209,332]. Alavi et al. further dive into these temporal scales of adaptation of the built environment (see Figure 8), unpacking the contemporary aspects of the speed of interaction – what they call microscopic mutations of adaptation- in smart buildings; discussing how data-driven adaptation impacts building occupants over time, and how knowledge can be extracted (and generalized) for the building occupants based on personal and non-personal data collected in the buildings over time [332].

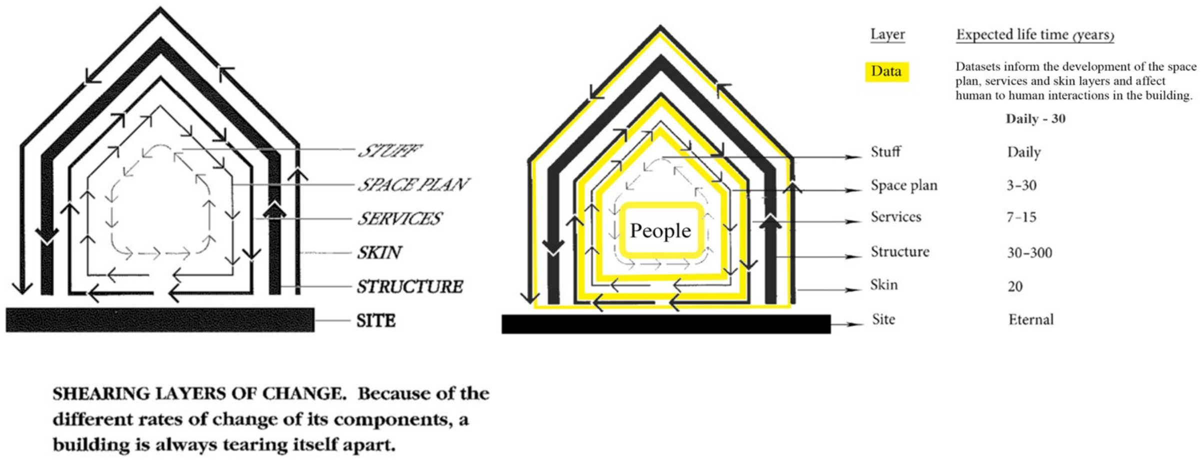

Figure 7: Shearing Layers by S. Brand, 1994 (Left) [34]; Revisited by Lachlan Urquhart, Holger Schnädelbach and Nils Jäger (2019) (appropriated by researcher) [377]

Human building Interaction is often intertwined with Adaptive Architecture research [189,404]- see for instance the work of Schnädelbach [329,331], Jäger [168,169], and Urquhart [374] (Figure 7). Adaptive Architecture [169,331,374] treats the aesthetic, physical and material dimensions of architecture as an interface [189,243,246,404] and an avenue to explore human-building interactions; following an embodied and enacted approach to understanding cognition and human behavior [168–170]. An example of such work is ExoBuilding [330]; a physiologically-driven adaptive architecture pavilion which served as a vehicle to unpack human behavior (synchrony) when exposed to bio-feedback. In their recent work [331], Schnädelbach et al. [331] discuss temporal and spatial design tensions when adaptive

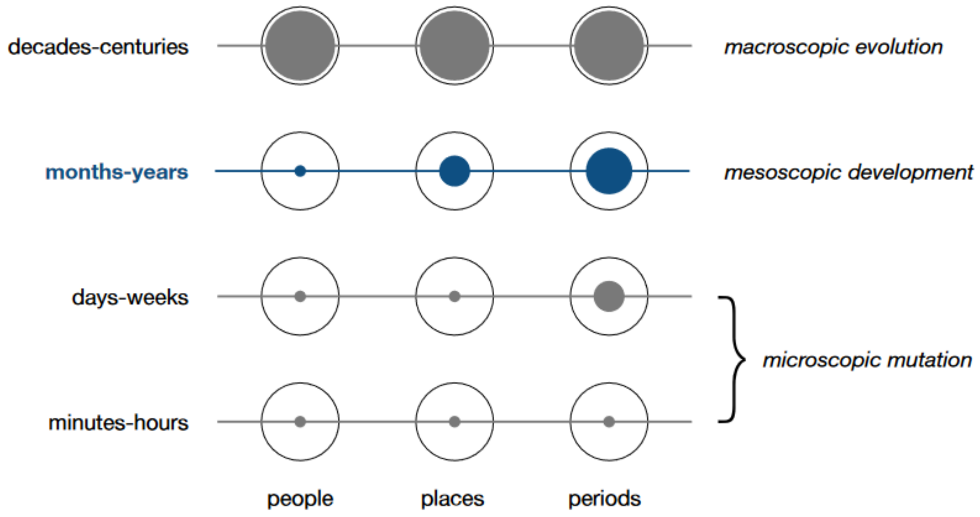

Figure 8: Alavi et al **[332]**; on temporal scales of adaptive architecture.

buildings and personal data are linked (contextualized within GDPR); to guide future design work of adaptive buildings driven by personal data [331,332]. The work of Nabil et al. on interactive interiors [240,242,243,246] is particularly sensitive with regards to aesthetics of adaptive architecture and the use of soft actuating materials [240]– which I will later unpack under the Soft Robotics & actuating materials [36] literature. Broader literature relevant to adaptive architecture as display [19,48,115,170] include works relevant to ambient displays and peripheral interaction [22,23,148,299,378,394], physical displays [199,226,249], shape changing displays [139,295,306], and calm and slow computing [386].

Finally, relevant HBI literature on data-privacy and the opportunities and pitfalls of technological infrastructure (sensing modalities) used in smart buildings is heavily informed by Ubiquitous computing (Ubicomp) research (see Figure 9)[185,193,257,385]. For instance, I refer to key works addressing Internet of Things (IoT) deployments in lived-in buildings and observed privacy concerns [26,99,257,420] – the Aware Home [185]; Neustaedter and Greenberg's work [257]; Langheinrich's Privacy by Design [193]; Nissembaum's Privacy as Contextual Integrity [260]; Beckwith's Design for Ubiquity [26]; or more recent works such as [99,420].

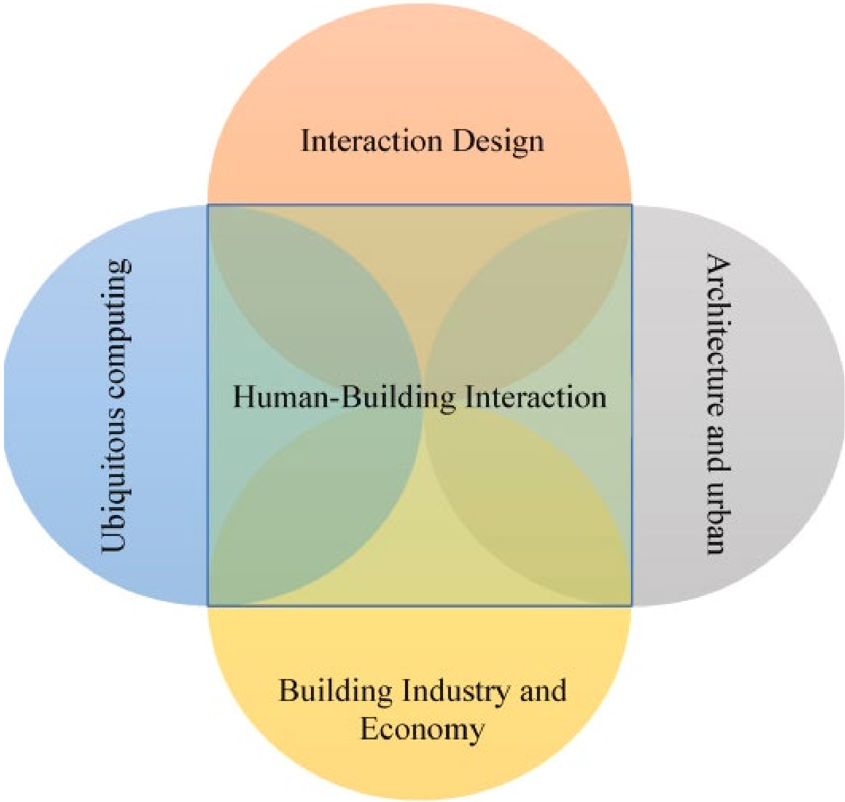

Figure 9: Chartography of HBI-relevant research fields initial by Nembrini and Lalanne **[254]**; revisited by Taherkhani et al. **[362]**

HBI research ultimately shifts the focus from 'smart buildings' and 'users', to a wider smart agenda towards achieving sustainability, meaningful usage, and wellbeing in the buildings together with their occupants [142,209,332]. Contributing to HBI research, this work is primarily concerned with the human values and experiences in lived-in smart office buildings; to guide the human-centered design of future workplaces. Moreover, a key theoretical positioning of this PhD work is the empowerment of the building occupants; i.e. the engagement of the building occupants with data in the buildings through feedback technology [215,216] to support them to gain awareness on what data is collected and how it is (or can be) used, and set the space for them to make informed choices (based on data) in the buildings –e.g. use spaces in ways that support their comfort in terms of temperature or air quality [236,253].

To help further map the HBI research space relevant to smart office buildings; the next section unpacks literature on the quantification of lived-in built environment, summarizes key research gaps and how this PhD addresses them.

2.1.1. Smart Buildings as Quantified 'Living Labs' and relevant Research Gaps (RQ1)

The phenomenon of lived-in quantification emerges as the result of the constantly increasing tendency to inhabit smart buildings [332]; referring to the intensive data-collection in smart environments [8,171,223,332]. More and more office and domestic environments are built to be permanently monitoring [8] using networks of sensors, collecting and processing a massive amount of data sets– i.e. environmental, post-occupancy, operational data, user-generated data from wearable bands or mobile devices [171,311,312,332] (see Newcastle future homes [25] for instance) – exhibiting highly quantified environments. While 'smart' focuses on the potentials of IoT and automation [44,171] -i.e. what do we do with the data-, the term 'quantified' addresses the form and scale of data collection prior to the complexities of processing and using it [96,223,247]. The industrial scale of the technological deployments and the fact that it concerns lived-in spaces - opposed to Ubicomp laboratories [175]- creates an unprecedented research landscape.

Drawn from the concept of the 'quantified self' [96,101,210,228,316], quantified buildings present a unique case; heavily employing industrial embedded sensors and often utilizing the widespread use of mobile and commodity wearable technology[98,145,210,228,247]. There are many cases that mobile or wearable data are collected and used in smart office buildings on the premise of enhancing comfort – see Edge hot-desking customization application [171], whereby users can store their light and temperature preferences and customize any hot-desk as they wish. Although consented, there are direct implications on the use of such personal data from the building's IoT infrastructure. As data tracking is spatialized, contextualized, and (opposed to self-tracking) extended beyond the 'self' and the selected community of interest [98,228,247,352]; quantified environments compose a highly complex emerging research agenda [222,223].

Quantified smart buildings can indeed provide the ground data infrastructure for further research in improving lived in spaces and the experiences in them. Referred as living-labs or lived-in Places following Alavi et al.'s categorization [8], some smart buildings are intentionally built as a real place and a research infrastructure in the same time [185] – e.g London PEARL Living Labs [26] for instance [8]. The envisioned HBI research outcomes of such living labs are interventions that bring value through supporting and enhancing the collective experiences [142,143,169] of their occupants in the long term [143,209,332,377]; empowering them through the use of accumulated data - for example, by visualizing sensed data to the building occupants [10,246,315,374,394]; support the health and wellbeing of their occupants [332]– e.g. data-driven restorative environments [345,353,410]- and improve the built environment and the life in it [75,142,332].

Still, there are plenty examples where the line between research infrastructure and lived-in smart building is hard to be drawn [8]. In some cases, what differentiates a living lab from a lived-in smart building is the data access and ownership, the access to the space and infrastructure, and the focus and scope of a potential research agenda for the place [332]. The

[25] https://newcastlehelix.com/residential
[26] https://www.pearl.place/

Edge described above [171] could be seen as such an example, as well as USB, the office building used in this work. The building[27] where the studies took place is a five-floor modern office building in a city in the UK, which has been advertised and is widely known as a smart building. It is a highly sensing and monitoring environment with an extensive array of embedded environmental and occupancy sensors. The building is part of Newcastle University, hosting office, teaching, event-space, and research facilities; while the ground floor is an atrium open to public and often serves as event space. Although not explicitly built as a research facility/living lab, the building works as such: it is built to both serve as a real workplace while providing opportunities to conduct research with the data. Data is logged publicly via an API[28], allowing open access to real-time and historical (timeseries) data of different spaces in the building.

The availability of the open datasets and access to lived-in quantified workplaces creates great opportunities and challenges for HBI research [142,254,317]. However, given the complexities of the lived-in instrumented environments; there is limited understanding of the occupants' primary concerns, values and experiences while inhabiting those spaces. As most of the past works in HCI/Ubicomp took place in purpose-made living labs and not in real lived-in buildings, there is great value in doing research to unpack the building occupants' experiences and considerations in these places **(RQ1)**; which is what this PhD attempts to do -see Chapter 4. The studies in real lived-in smart office buildings are very limited [8]- as many of them are highly inaccessible- highlighting the contribution of this PhD as it evolves around a lived-in smart building.

Broader present challenges of lived-in quantified spaces relate with data sharing -i.e. what and how data is shared between individuals, and between individuals and the organization data visibility – i.e. what data is the user able to experience in the building and how - data use – i.e. applications for wellbeing and collective life - data control, and ultimately, the privacy of the building occupants [99,207,284,420]. I will further unpack the key relevant literature, research challenges (and research gaps), together with how this PhD contributes to addressing some of those challenges (and research gaps) in the following section.

2.2. Overview of HBI research for quantified buildings for work (RQ1, RQ2, RQ3)

I sketch out below some relevant background research taking place in smart buildings as living labs[8] with a focus on office buildings, to foreground the studies and findings discussed in the next empirical chapters. Literature below is drawn predominantly from the field of Human Building Interaction [9,143,332] and Adaptive Architecture [331,377]. Many of the works below address data collection in the office buildings through technologies that seek to engage occupants with data in the buildings [10,187,422]. Key themes in the literature include data collection and use for supporting wellbeing and social life in the buildings [42,332], and more recently pollution [25] and sustainability [27,56,89,337,365]. There is a particular focus on

[27] https://www.ncl.ac.uk/cesi/research/demo/usb/

[28] https://api.usb.urbanobservatory.ac.uk/ and https://3d.usb.urbanobservatory.ac.uk/

wellbeing-related research for the purpose of this PhD, which will be unpacked further in Section 2.2.1.

In the works below, there are different approaches to data collection observed; some studies follow an 'instrumented people' approach [8]– i.e. using wearable tracking devices– whereas other use passive sensing or deploy interactive prototypes to facilitate data collection and engagement in the buildings [185]. In terms of data use, many works explore means to create awareness through public and shared [24,298,378], ambient [114,148] and physical [10,156,406] displays; including literature on adaptive [169,331] and media architecture [109,238,394], and shape changing displays [199,249,275,363]. Many works below often deploy their interventions in lived-in offices for longer periods of time [8,185,370]; with a view on informing human-centered smart offices.

The studies in real lived-in smart buildings are very limited [8]. This highlights *the key contribution of this PhD, as it revolves around a lived-in smart building and the understanding the occupants' experiences* ***(RQ1)*** *with a view of informing the human-centered design of these places* **(RQ3).**

Physical space and its impact on perceived and actual privacy in smart buildings a highly vague and complex matter in HCI and Ubicomp research [26,99,193,257], where lies one of the contributions of this PhD **(RQ1)-** e.g. see Chapters 4,6. The reality of lived-in smart office buildings has unresolved complexities with regards to their users' experiences, such as the feeling of control on their environments [231,232], and perceived and actual privacy [26,133,193,260]. Mentioning relevant work, Nepal et al [255] have explored the benefits of use and privacy concerns on passive sensing in the workplace; unpacking that the lack of control over the sensor data collection was a significant privacy concern [255]. Other work includes research on changing perceptions on data in the workplace and privacy concerns [68,90,133]; and works on informing consent processes for smart buildings [5,133,207,284,392]. The issue of data invisibility and lack of any control over when & where data is collected is one of the key problems in the smart workplace, which recent works attempt to address through various ways including tangible interfaces [6, 134]; however very little work refers to the workplace. Reflecting on present research gaps around privacy, the underlying issue stems from the perception territory, and the ability to control physical & digital boundaries (i.e. the pace of data collection in spatiotemporal scale); which is often not the case in smart offices. Some recent works attempt to address the issue of territory – see WaddleWalls [275], a robotic room divider for customizing visual privacy at the workplace – albeit without addressing the issue of customizing data collection in place. Yet more research is needed on understanding the impact of physical space on perceptions of privacy in smart buildings **(RQ1)**; to guide the design of interventions that bring the physical and the digital/data dimensions together and in ways that can be customizable by occupants**.** Achieving data awareness and acceptability of data collection practices from the building occupants of smart buildings remains an open challenge, where lies a key contribution of this PhD work **(RQ1)**. This PhD contributes to these research gaps primarily in Chapter 4 and Chapter 6.

Advances in sensory and computing power in the buildings are giving rise to increasing opportunities for ambient and physical feedback in the buildings. Beyond monitoring, researchers have deployed a variety of technologies and artifacts to surface data in office buildings, to engage their occupants and unpack aspects of their experience of data in-place [332]. Highly relevant to workplace, various types of ambient systems can present information in the periphery without distracting or burdening the building occupants [22] for awareness purposes - see shape and color changing displays [199,226,249]. Examples include physical and ambient displays [23,114,148,299,394] sometimes embedded in the building's existing infrastructure – i.e. using interior decorative elements such as room dividers [71,242,246] walls and windows [19,396]– or using objects commonly used in the building – lamps, lights etc. [287,373]. A lot of these works focus on communicating information in an aesthetically pleasing and calm manner [22,206,386] – see slow data physicalizations [140,226]. The research on physical and shape changing interfaces are only mentioned briefly here, as they will be extensively discussed in Section 2.2.2.

Light as data feedback is manifested in a breadth of related research [287,375]. Relevant projects engaging with programable light LEDs such as Philips Hue [84,285] in different scales in the buildings- see Media architecture [48,115] and LEDs for large displays [125,154,229]. A relevant project is Low-res [154] for instance where light is used in different configurations as part of architectural elements. Relevant to the use of light, augmenting information on static architectural elements through AR and projection technologies has been the focus of several works [15,163,197,229]. Examples are projects on augmented barriers for blocking distractions [197], or office lamps that extending display and working areas in the periphery [162,163,393] - see LumenAR and FACT using mobile projectors [162]. Projection can also work in large displays [290,296,299,418] - see ASPECTA Toolkit [296]. This PhD takes a novel approach exploring light feedback together with shape-changing elements to physicalize environmental data **(RQ3);** unpacking relevant literature in Section 2.2.2.

In the workplace, shape-changing displays have been employed to enhance safety and privacy, support with collaboration and productivity, and for enhancing visual and physical comfort [15,197] social awareness and human-to-human interaction– see the work of Leithinger [112,199,249], Petersen and Grønbæk [138,139]. Takashima [363,364] particularly focused on large scale displays for the workplace; including TransformTable [363], a shape-changing table, and a wall shifting display [367]. Based on the notion of affordances,Grønbæk et al [137,139] explore the potentials of shape changing furniture to support social interactions in shared informal meetings - see KirigamiTable [139], a shape changing meeting table and an interactive display for co-located collaboration, creating opportunities for dynamic socio-spatial interactions. Many of these works include interactive and shape changing furniture [137,139] and DIY smart furniture – see Foxels [291]. A different approach is illustrated by SenseSeat [52], a computational multisensorial seat that can be digitally controlled and vary the frequency and intensity of visual, auditory, and olfactory stimulus; creating furniture that enable control the ambient surroundings for personalized comfort. Many of these past works on physical interfaces address tangible feedback [139,249]; with recent works employing actuating textiles [120] and robotics – see WaddleWalls robotic room divider for instance [275].

This PhD takes a novel approach to designing large scale shape-changing displays for data awareness in the workplace **(RQ3)**, particularly focusing on biomimetic structures and soft-robotic interventions. Relevant background literature and research gaps are framed in Section 2.2.2.
Relevant with improving the experience of the building occupants in smart buildings; research for wellbeing in smart office buildings is a field rapidly evolving [145,187,228] **(RQ1, RQ2).** For instance, a large body of past work is concerned with indoor climate in the office spaces [16,349,357], it's impact on productivity and wellbeing, and the most appropriate ways to sense, communicate and engage the building occupants in co-shaping it [10,70,156]. Beyond indoor climate, other works have accomplished an understanding of how the design of the built environment cam impact social interactions [219,222,223,332]. Relevant literature and research gaps are unpacked in the Section 2.2.1.

Relevant research on integrated wellbeing [100,353] has informed contemporary building design practice– see WELL[29] certificate (Section 2.2.1.)- as well as the development of diverse IoT technology to communicate and collectively manage data for wellbeing in offices [10,16,70,90,171,349]. Still these two dimensions – i.e. the physical design and data integration - do not meet as much as much they could. Open challenges remain around physical design and materiality in smart buildings, wellbeing, and the development of building-integrated technology that empowers building occupants in terms of wellbeing. This PhD contributes to addressing some of the challenges around improving the human experience in smart buildings through addressing the 'merging' of the physical and digital dimension of such spaces **(RQ1),** by designing and deploying a physical intervention **(RQ3)** and evaluating it in-place with the residents of a building **(RQ1)**. The following section is dedicated to further unpacking relevant literature on wellbeing in the buildings for work **(RQ2);** literature gaps and how this PhD addresses some of those.

2.2.1. HBI research and Wellbeing: related research for the workplace (RQ2)

Research on wellbeing at the workplace spans across many factors; including environmental wellbeing [308,350] – i.e. light, noise, temperature – physical activity [102,114] and ergonomics [159,283], and emotional and cognitive wellbeing [31,219,359]– including social interactions and collaborations in the workplace [9,377]. I briefly highlight relevant examples from HBI, HCI and Ubicomp literature that address aspects of wellbeing in workspaces (both office and domestic) following PROWELL[30] wellbeing dimensions; which broadly relate to

[29] https://www.wellcertified.com/

[30] See PROWELL Key Performance Indicators (KPIs) of wellbeing at the physical workplace at https://www.innovativeworkplaceinstitute.org/workplace-wellbeing-prowell.php .

physical – e.g. physical comfort, physical activity- environmental – e.g. noise, air quality- social and emotional wellbeing- e.g. stress.

Bringing the focus to how the physical design of the workplace – i.e. the buildings for work - can support or inhibit aspects of wellbeing, relevant work focuses on the impact of architecture and the physical space on wellbeing and human behavior [9,262,359,424]. For instance, see the broader work of Sternberg [353], or Alavi's Hide and Seek in the workplace [9,377]. Often utilizing wearable sensory devices, many works have accomplished an understanding of how the design of the built environment impacts social interactions [219,222,223,332]. Researchers have employed different technologies to unpack relationships between group behavior and physical environments, including passive & active sensing such as ambient sensors, wearables and mobile phones [145,255,356]. Some studies have used wearable badges to track social interactions in a workplace [9,42,332,377], to illustrate how the physical design of workplaces supports or inhibits specific types of interactions, how different behavioral profiles thrive in specific spatial configurations [9,332,377], and how an organizations' physical design combines with organizational structure [42].

Physical space and its impact on wellbeing brings research from environmental psychology, public health[86,110,308], architecture and engineering [86,100,308,350]. Relevant research also extends on biophilic design for office spaces and its impact on wellbeing [43,213,424]. Wellbeing is also linked with the perception of privacy in physical space[251,260]; in which, the physical design of the workplace plays a big role.

Passive data collection in the built environment through smart phones, wearables and embedded sensors to assess wellbeing is broadly utilized by relevant past HCI research [45]; with projects employing such technologies to monitor mood and emotional wellbeing [47,69,121,146,219], stress [3,127,146,410] and physical activity of the building occupants [51,81,114]. The SEBA system [62] is an example of an approach for monitoring psychological stress continuously at the workplace using wearable sensors. Some of these projects have been criticized for the use of sensitive (i.e. personal) data in the workplace [45,62,87,145] and the fact that they often fail to proactively engage the users in utilizing their data for their own benefit through appropriate feedback mechanisms [156,313,315]. The importance of feedback on wellbeing at the workplace has been addressed by several studies, looking at deploying persuasive technologies for behavior change at the office [54,167,206,234,287,315] – for instance, the work of Ludden and Meekhof [206] on calm persuasive thechnology to take breaks from work, or STARS [287]– a project using ambient lights on the ceiling to manage noise in large shared offices. Finally, a few studies explored the impact of wellbeing self-tracking and sharing on the individual and collective wellbeing in the lived workspace [69,98,228,236], albeit without addressing ambient feedback in that context.

A large body of past work is concerned with indoor climate in the office spaces [16,349,357], it's impact on productivity and wellbeing, and the most appropriate ways to sense, communicate and engage the building occupants in co-shaping it [10,70,156]. Physical comfort [6,10,74,208] – including environmental, thermal, visual - is a key relevant term throughout literature, with studies addressing multiple aspects of the perceived indoor climate and developing technologies to support the environmental wellbeing of the building occupants [83,187,422]. This primarily includes awareness technologies – i.e. technologies that provide awareness on aspects of indoor climate to unpack personal comfort (see for instance ComfortBox [10]) and negotiate with others (see ThermoKiosk [70], a study about the differences in thermal comfort of the occupants of a shared office). Alavi et al. addressed the multidimensional issue of comfort in the workplace through Comfortbox [10]- a sensing physical display of environmental data, engaging the office space occupants in gaining awareness on their embodied comfort. Many of these technologies simultaneously facilitate data collection (e.g. environmental) and data awareness [10,70,338] – see for instance ComfortBox [10].

Recent studies look at the impact of air quality (AQ) on wellbeing [192,221,262,308,357], employing monitoring systems [360] and nature based solutions [223] to monitor and improve AQ; or using awareness technologies (e.g. notifications and visualizations) to support wellbeing and study the collective behavior of occupants of office spaces [343,422].
Research on interventions for environmental wellbeing - particularly associated with AQ - became highly relevant during the COVID-19 pandemic; with AQ awareness and control in the workplace becoming a pressing matter [25,83,187,343]. Beyond COVID-19, interventions for AQ awareness are broadly relevant with the building occupants' wellbeing [349,424], sustainability [126,365] and climate-sensitive behavior [89,344]– i.e. within the scope of technologies that foster climate awareness in the buildings with the prospect of prompting building occupants to rethink human-climate relationships, and how their own behaviors and actions can impact climate in the buildings. Within that research space, relevant projects explore different forms of environmental data feedback – see for instance Atmospheric Interfaces [41,104]; ambient AQ notifications in smart rooms [83]; AQ route recommendations [341] etc. Hilo-wear, a predictive wearable notification system for indoor AND outdoor AQ (CO2) in office spaces [422,423] notifies the occupants of an office space to open the windows when indoor air quality reaches a critical point, given the outdoor pollution is low. The work of Kim and Li [187] addresses ambient light as air quality feedback and its perceivability as eco feedback. Dang et al. [83] explore different forms of ambient air quality notifications for smart rooms, addressing user experiences and expectations of indoor air quality visualizations. In a different approach, other works address environmental and emotional wellbeing and climatic concerns through employing biophilia when designing for the workplace – see [213,424]. Regardless of the recent attention air quality has obtained within HCI/HBI literature, it is still a relatively unexplored aspect of indoor climate, where this PhD work offers key contributions. Research gaps are around the building occupants experience air quality; what are the key air quality factors are key shaping their experience (i.e. humidity, CO2, temperature)[194] and how to visualize/physical air quality in the buildings **(RQ2, RQ3).**

Light has been probably the most studied environmental aspect for wellbeing in the workplace [161,211,373,375]– including the impact of natural light [161,373], and light pollution[76,211,375]; and the most explored medium for ambient feedback in the context of environmental [187], physical [114,287,315] or emotional wellbeing [285,345,373,410]. Many projects are coupling light with feedback to promote movement and physical activity in the workplace [114,287,315]. Light as biofeedback (generated by wearable sensors measuring arousal levels) was used to explore the implications of wellbeing awareness in the workplace - see "MoodLight"[345] or "DeLight"[410]; also as a means to create social connectedness [211,285] "DeLight" explores the potential of Philips Hue to support de-stressing, relaxing, and encouraging better breathing patterns. Light as feedback for physical activity and reduction of sedentary behavior is present in many works [39,81,114,147,167]. A relevant example is Yvonne Rogers' [315] data displays for employees' sedentary behavior; exploring different ambient and physical displays including lights, screens and pendants as physical displays to communicate physical activity data and the impact on employees' behavior [315]. In this PhD I take a novel approach exploring light feedback to represent air quality data, to indirectly support aspects of wellbeing in the built environment **(RQ2).**

The recent focus on remote and hybrid workplace wellbeing mainly addresses aspects of emotional wellbeing and social wellbeing/collaboration aspects [18,78,92,106,314]– see Fan et al. [106] research on subjective well-being associated with shifting places of work, they identified four patterned constellations of well-being based on burnout, work–life conflict, and job and life satisfaction. Plenty of research on the remote and hybrid focuses on meetings [53,78,191,314,318]; leaving the discussion on spatial and physical aspects, and environmental considerations for wellbeing broadly unaddressed; hence the motivation and one of the contributions of this PhD work [216] **(RQ2)**. The following section (2.2.1.1.) focuses on relevant background on the remote and hybrid workplace wellbeing.

2.2.1.1. The remote and hybrid workplace and wellbeing challenges

Lockdowns initiated during the COVID-19 pandemic have established the home as a permanent workspace for many [105,176,181,183]. The domestic spaces in which this remote work is conducted are generally limited and congested [105,216]. The remote home worker is thereby physically based in a highly unregulated and heterogeneous domestic space – a space for which separation of work and home is a challenge [106,216,351,369]. Remote workplace collaboration occurs predominantly through technological media; with all social activities reduced to 2-dimensional screens [351]. This raises challenges of remote home workers feeling both isolated and yet constantly connected [18,106,351], struggling to keep a balance between a domestic and technology mediated work-life [369].

Digital transformations have contributed to eliminating physical movement in the workplace [39,51,66,81,315] through enhancing connectivity between remote workers [18,84,141], and intensifying technology-mediated collaboration [78,217,256]. The use of such collaborating technologies does not mediate the benefits of informal, face-to-face interaction

[53,82,137,139,191], as well as physical activity for the wellbeing of the remote workers [81]. Lack of physical activity has resulted in ongoing health problems amongst connected remote workers [81,141], including chronic mental health issues [141] and physiological problems [81]. Past work in HCI has outlined some of these issues with a particular emphasis on work stress [3,31,55,127,410], low productivity and motivation [102,218], leaving the home office broadly unexplored. This highlights the contribution of this PhD work, as it brings the focus on the remote domestic workplace and discusses implications for data collection and physicalization in that context **(RQ2, RQ3).**

Within the context of remote workplace, the argument for ambient feedback [83,114,167,287,410] to support the remote home workers falls into place; illustrating the relevance and contribution of this PhD **(RQ2, RQ3).** Ambient systems have been previously used to mitigate 'always-on' environments [148,206,373], and to support cognitive, emotional and physical wellbeing in various domestic and health applications [206,345,373,410]. New directions in ambient spaces research emphasize on engaging the occupants through wearable-mediated feedback [134,145,147,356,422] and address contextual privacy through passive data collection [255]. Recommendations and predictions of the behavior of the building occupants to support wellbeing (relevant to Human -AI interaction research) are discussed in a small number of recent works [347,423], showing much potential while raising ethical concerns.

With past literature focusing on conventional office spaces [9,10], productivity or stress [74,410]; there are many unexplored potentials for ambient technology in the remote and hybrid workplace (i.e. the domestic and shared workplace) which this PhD attempts to address through Design Research **(RQ2, RQ3).**

To further contextualize dimensions of wellbeing in the built environment and the work that has been done in this PhD to address those through Design Research **(RQ2, RQ3),** the next subsection briefly addresses current relevant frameworks and their application on assessing wellbeing such WELL and PROWELL.

2.2.1.2. Integrated Wellbeing and models of assessment (WELL, PROWELL)

Wellbeing in the built environment and recently, in the hybrid workplace, has been the core work of Esther Sternberg [353]; framed under integrative health and its connection to the built environment [100]. Integrative health is defined as "healing-oriented medicine that takes into account the whole person, including all aspects of lifestyle, " and includes seven core domains: sleep; resiliency; environment; movement; relationships; spirituality; nutrition. Sternberg [353] and Engineer et al.[100] connect these seven integrative health domains to the built environment, understanding the built environment and human health in layers (see Figure 10), and unpacking how these layers corelate in forming a holistic approach to wellbeing (see Figures 11, 12). Moreover, they suggest specific building interventions that enhance and support healthy lifestyles and wellbeing such as access to natural lighting, views, connections to nature (biophilia), indoor air quality, control of one's environment, and spatial layout; aiming to guide design professionals in doing interventions to support each of the seven integrated health domains, and health professionals in understanding how elements of the built environment design can support holistic health [100].

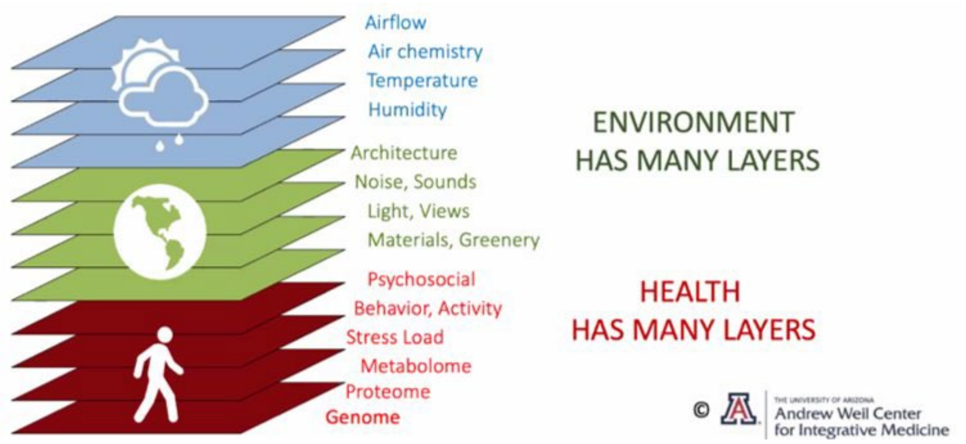

Figure 10: Sternberg's **[353]** Environment and Health layers

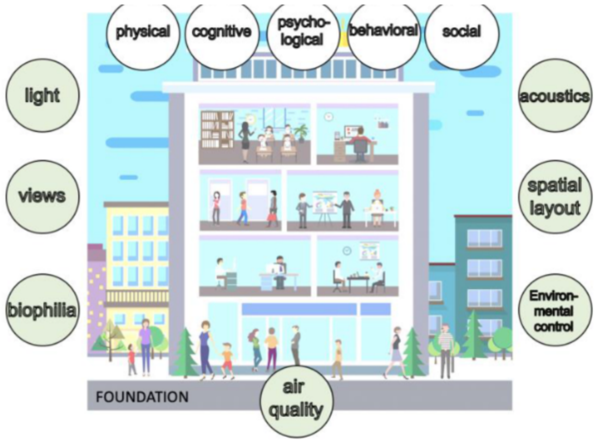

Fig. 2. A framework for impact of the built environment on health. Air quality is shown at the foundation because it is essential for health. Many other environmental attributes are essential for optimal wellbeing in the built environment. Source: Author.

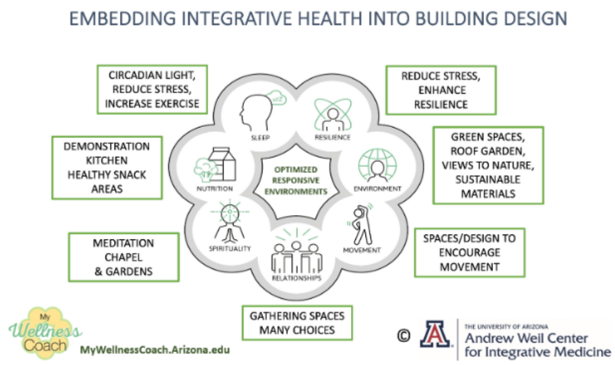

Fig. 3. Seven domains of Integrative Medicine. Source: Modified by Author from The Andrew Weil Center for Integrative Medicine, University of Arizona, My Wellness Coach App 7 Core Areas of Integrative Health [3].

Figure 11: Sternberg's **[353]** integrated health framework, illustrating how different layers corelate.

In her recent work, Sternberg[34] foregrounds these seven key domains into principles to create a workplace that fosters wellbeing in any place – with direct references to hybrid working.

[34] https://www.psychologytoday.com/us/blog/creating-wellbeing-wherever-you-are/202308/creating-wellbeing-spaces-to-de-stress-and-keep-you

These are *Resilience:* reducing noise, avoid working in noisy spots and keep humidity and noise levels in middle range; *Movement:* creating spaces that encourage physical activity; *Sleep:* natural light to encourage circadian patterns; *Relationships:* create opportunities to gather with co-workers; *Environment:* bring nature indoors & have access to nature outdoors; *Nutrition:* consume food that helps alertness and focus; *Spirituality:* visit spaces for calming, recharging and restoring breaks. Some of these aspects have been suggested by broader literature on wellbeing broadly [50,176,220,281,292] as well as workplace and remote workplace wellbeing [106,176,216]. For instance, see Calvo's and Peter's Positive Computing framework [50], Joyce's work on flexible working and the impact of social support on health [176]; or Mata's work around improving indoor air quality through nature based solutions [221].

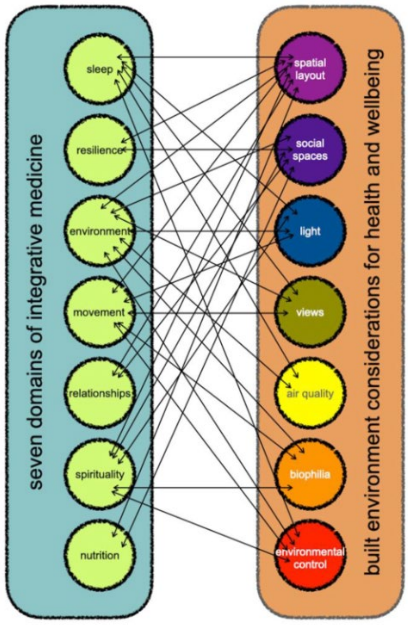

Fig. 8. Web of connections between the seven domains of integrative medicine and built environment considerations for health and wellbeing. Source: Author.

Figure 12: Domains of integrative medicine and built environment considerations **[353]**

The above research has driven contemporary building design through the development of building standards to assess and evaluate building design. WELL certification[35] has been a leading standard for ensuring wellbeing in the workplace. It consists of ten key concepts (see Figure 13); each of which further develops into criteria for assessing the building's design and performance. WELL is a performance-based system; assessments involve on-site testing of building performance[36]. Although considering cognitive and social wellbeing, the primary focus of WELL is the building's infrastructure and systems performance measurement to inform knowledge on the human health -environment relationships. It can be described as a quantitative, top-down and performance-oriented model; that does not necessarily include

[35] https://www.wellcertified.com/

[36] The process for on-site assessments and testing is called Performance Verification. On-site measurements are taken for various air and water quality parameters, as well as sound and light levels. It is a distinct process from traditional building commissioning and assures that the building performs as intended, according to WELL requirements.

mixed methods research – e.g. surveys or qualitative assessment of the experiences of the building occupants.

Figure 13: Key dimensions of WELL model for wellbeing in the built environment

Another model that is focused on assessing wellbeing in the workplace – and in-directly the building's design and capacity to foster it is PROWELL model[37]. PROWELL is one of the most comprehensive models for assessing wellbeing in the workplace. It provides a comprehensive list of seven (7) Key health & wellbeing Performance Indicators (KPIs) for the workplace; encompassing three major dimensions of wellbeing: physical – including environmental wellbeing, physical comfort, physical activity and nourishment; social wellbeing and mental wellbeing – including emotional and cognitive wellbeing (see Figure 14). PROWELL is essentially an analytics platform; providing practitioners with an online tool to assess wellbeing. It is built on dimensions similar to the key WELL concepts; but it extends beyond building performance to evaluating organizational culture. Although not explicitly framed around the built environment[38]; it is used by researchers for evaluating how the built environment supports or inhibits wellbeing - see relevant research by UCL based on PROWELL application; combining on-site assessments, surveys and sensory data[39].

[37] https://www.innovativeworkplaceinstitute.org/workplace-wellbeing-prowell.php
[38] Innovative Workplace Institute also provides architecture-oriented design evaluation of workplaces; with criteria such as Indoor Air Comfort, Thermal Comfort, Visual Comfort, Acoustical Comfort, Ergonomics etc.; which map on the key dimensions of PROWELL- i.e. physical wellbeing (comfort, fitness), environmental wellbeing, emotional and cognitive wellbeing, and social wellbeing.
[39] https://www.ucl.ac.uk/bartlett/environmental-design/workplace-health-wellbeing-linking-environment-employee-health-wellbeing-workplaces

Figure 14: PROWELL model of wellbeing assessment

To date, there are no specific tools to bring these building design dimensions to the hands of HCI researchers; with the prospect of designing physical interfaces in the architectural scale that support wellbeing dimensions. This research gap is addressed by this work at Chapter 06 **(RQ2, RQ3),** to drive the design of interventions in that space – i.e. in the context of quantified buildings and to support wellbeing in the workplace.

Designing and developing interventions as a response to empirical findings on the building occupants experiences is a key part of this work and one of its contributions. To contextualize the Design research that took place, the next section unpacks literature around ambient and physical interfaces in the buildings – including Adaptive architecture and Shape changing interfaces - to support decisions made with regards to the intervention I made (to surface environmental data) and highlight its novelty **(RQ3).**

2.2.2. Designing Physical feedback for quantified buildings (RQ3)

This section provides a brief overview of theories on feedback perception and relevant research on physical and shape changing displays, including adaptive architecture as display; a brief history of biomimicry & biophilia in adaptive architecture and physical/shape changing displays, and introduces soft robotics & actuating materials design agenda illustrating their application on adaptive architecture and interactive interiors.

2.2.2.1. Feedback perception and physical / shape changing displays

Research on physical and ambient feedback in the buildings comes from the field of public and shared [24,298,378], ambient [114,148] and physical [10,156,406] displays; including literature on adaptive [169,331] and media architecture as display [109,238,394]. Broadly, physical data displays utilize physical (form, shape, shape change, color) and material (including light) properties to communicate data in-place [41,71,249]. Works on physical displays include shape changing furniture and tangible interfaces – see the broader work of Leithinger [112,199,249], Petersen [295], Grønbæk [138,139] and Takashima [364]. Such works utilize shape (and often color) change to foster human-to-human interactions in various contexts; see for instance KirigamiTable [139], a shape changing meeting table and an interactive display for co-located collaboration, creating opportunities for dynamic socio-spatial interactions.

A category of physical displays are data physicalizations [14,153,172]– see for instance PhysiKit [156], Shutters [71], or Yo-Yo machines [123]. Such works often include more abstract representations of data utilizing material properties; explore aspects of scale of data, either physical [204,326] or temporal -see slow physicalizations [140,226,266]; engage with tangible interaction [153]; or embrace DIY [48] and user customizability [156]. Shutters [71] is an example of such a physical display of air quality (AQ) data in a workplace building, engaging with three-dimensionality of material shape change at the architectural scale to communicate data. Shutters employs Smart Memory Alloy (SMA) wires integrated in fabric room dividers, which actuate shape change of the fabric elements based on data streams. The result is a large scale physical display, which indirectly communicates information on air quality visible when natural light drops. Besides this project, the potentials of such actuating materials – framed under soft robotics & actuating materials agenda - to provide physical or haptic feedback at large scale are relatively unexplored; highlighting the contributions of this PhD **(RQ3).**

Much of past literature on peripheral interaction [22–24,148] extended to the design of ambient / physical feedback [299,378,394] including shape changing displays and adaptive architecture is based on cognitive theories of environmental awareness and perception[41] [110,155]. A key theme, illustrated in many works on data physicalizations, is that data awareness is key aspect to further impact behavior and support wellbeing. The term ‘awareness interface' illustrated in slow [140,206,267] and calm computing [177,313,386], and ambient/physical feedback literature is based upon this premise that, by bringing awareness on data through designing relevant physical feedback, an opportunity for conscious action and behavior change is created [54]. Awareness feedback in slow and calm computing [140,206] is feedback that does not monopolize attention; presenting information to the building

[41] Models of understanding the perception and experience of space come from environmental psychology [110,155]. Environmental perception has commonly been defined as awareness of, or feelings about, the environment, and as the act of apprehending the environment by the senses. In studies of environmental perception and cognition, the existence of motives, goals, and attitudes toward action alternatives are usually taken for granted, and the psychological responses or processes mediating between the environment and actions are made a primary focus. These processes include the picking up of information from, and about, the environment; the internal, perceptual, and cognitive representation of the information; and judgments, decisions, and choices made on the basis of the represented information.

occupants in a respectful, meaningful, engaging but non-manipulative way [54]. The question for design research then lies on what and how physical and material feedback can be designed to better support awareness – different aspects of awareness- and data experience in -place; which is a key research contribution of this PhD work (see Research Question 3, Chapter 7).

With regards to shape changing displays and adaptive architecture as physical feedback; it is important to mention the notion of affordances [112,295,306]. Initially developed by Gibson[42] [387], the notion of affordances can be described as the quality or property of an object that defines its possible uses (degrees of freedom) on how it can or should be used. Alike, physical shape changing displays treat the physical properties of the environment as mechanisms to invite building occupants towards certain (inter)actions [173,376]; which on the long term, might enhance or inhibit specific contextualized behaviors[43] – see for instance, "The End of sitting"[44] [395]. The notion of affordances is the basis of enaction theories – the idea we learn through interacting with the physical space [112,212,376]– which are leading key Adaptive Architecture paradigms [168–170].

Recent research on feedback awareness, perception and experience in place brings theories from environmental and cognitive psychology [155,169,348,359] and neuroscience [282] in Architecture and HBI research; addressing ways to connect neuroscience and the study of the human behavioral responses to the built environment. New developments in these fields[45]

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[42] According to a theory developed by the influential psychologist James Gibson, daily life entails engaging with and enacting the "action possibilities" of the environment, which he calls "affordances."[376,387] Affordances are possibilities for action offered by the environment—an environment which, in the case of humans, is to a large extent designed. Many interpretations of this theory of affordances are tied to motor behavior, such as the fact that something—like a cup or a book—can be grasped because of its dimensions, shape, texture, etc., or that the relatively horizontal, structurally supported, elevated surface of what we call chairs allows one to sit on them [212,295]. However, affordances do not only depend on the way our environment is designed, but also on people's abilities and thus on the patterns of activity that have been cultivated by sociocultural practices. The affordance of sitting on a chair, for instance, exists only against a wider background of sociocultural practices of sitting on chairs, rather than sitting on the floor, on carpets, or perhaps living in a non-sedentary way altogether [395]. To emphasize this social, or rather sociomaterial, nature of our environment—meaning we cannot clearly separate material and social spheres—we can understand affordances as relations between aspects of the sociomaterial environment and abilities available in a form of life [212,295].

[43] In this philosophy of affordances, a form of life (including the human one) is not static, but rather consists of behavioral patterns manifested over time which can be changed by offering alternative or different affordances[387]. This is crucial because it allows for ways of generating behavioral change to be conceived. Because of their dependence on affordances, sociomaterially patterned practices, like the practice of making sedentary environments as opposed to the practice of making environments that support standing, should not be seen as a static given, but as changeable. This means that architects and designers do not only make new objects or buildings, but can also create new affordances that have the possibility to alter patterns of human activity, and might even change entire sociocultural practices [212,387].

[44] The End of Sitting confronted government planners with an alternative vision for the office of 2025, in which there are no chairs or tables, but rather a landscape of inclined planes to support different standing and leaning positions, i.e., affordances for supported standing/leaning. The installation matches a variety of different body lengths, and invites people to stand, lean, and recline in the context of work, where such working positions, the installation makes people aware of the way their bodies normally take certain environmental regularities for granted [395].

[45] Traditionally, architectural practice has been dominated by the eye/sight. In recent decades, though, architects and designers have increasingly started to consider the other senses, namely sound, touch, smell, and on rare occasions, even taste in their work. As yet, there has been little recognition of the growing understanding of the

recognize the multisensory nature of spatial experience and support a more holistic and embodied[46] [391] view than a merely visual-driven one [282]. Among the many topics related to multisensory perceptual integration and embodiment, the concept of hapticity was recently introduced, suggesting a pivotal role of tactile perception and haptic imagery in architectural appraisal [282]. Such knowledge can have specific application in design research for large scale physical displays, adaptive architecture as display and shape changing displays; emphasizing the importance of material properties and three-dimensionality [157] to address holistic (and embodied) experience. This work is inspired by these theories, exploring materiality, light and 3-dimensional shape change as a means to provide air quality feedback in large scale in the buildings **(RQ3),** and providing insights from the building occupants experiences when interacting with the intervention **(RQ1, RQ3).**

Exploring further relevant research on materiality and form factors for the purpose of designing physical feedback; the next subsections are dedicated on a short overview of biomimicry and biophilia in architecture and interaction design and its impact on human behavior. Biomimicry/biophilia is a concepts that emerged through the epirical findings of this work -see Chapter 6 – which has high relevance to designing buildings that support wellbeing (i.e. biophilic design) as well as to the literature on imitating nature to support calm physical feedback (i.e. biomimicry). For the above reasons, key works in biomimetic/biophilic design are unpacked below to illustrate how this PhD relates to these two concepts.

2.2.2.2. Biomimicry and Biophilia in Adaptive Architecture & Shape changing interfaces.

Biomimicry and biophilia as concepts for designing buildings have a long history [180,213,286,424]; with recent examples addressing the role of innovative materials [39,46,83] and bio-inspired systems [286,424] in enhancing wellbeing in the built environment [286]. Biophilia and biomimicry are alike in their fundamental focus on what might be called 'nature's

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multisensory nature of the human mind that has emerged from the field of cognitive neuroscience research. Only by recognizing the fundamentally multisensory nature of experience that one can really hope to explain a number of surprising cross-modal environmental or atmospheric interactions, such as between lighting color and thermal comfort or between sound and the perceived safety of public space. The work of Charles Spence [110,348] maps existing problems and opportunities within the space of architectural design, hoping for a future that building's design based on the understanding of multisensory experience can better promote our social, cognitive, and emotional development, rather than hindering it.[119,282,348]

[46] Embodied Cognition theory is a movement in cognitive science that grants the body a central role in shaping the mind. In the words of A. Wilson [391], key claims of embodied cognition are that 1) Cognition is situated: Cognitive activity takes place in the context of a real-world environment, and it inherently involves perception and action; 2) Cognition is time pressured and is understood in terms of how it functions under the pressures of real-time interaction with the environment; 3).We off-load cognitive work onto the environment. Because of limits on our information-processing abilities (e.g., limits on attention and working memory), we exploit the environment to reduce the cognitive workload. We make the environment hold or even manipulate information for us, and we harvest that information only on a need-to know basis. 4) The environment is part of the cognitive system. The information flow between mind and world is so dense and continuous that, for scientists studying the nature of cognitive activity, the mind alone is not a meaningful unit of analysis; 5) Cognition is for action. The function of the mind is to guide action, and cognitive mechanisms such as perception and memory must be understood in terms of their ultimate contribution to situation-appropriate behavior; 6) Off-line cognition is body based. Even when decoupled from the environment, the activity of the mind is grounded in mechanisms that evolved for interaction with the environment—that is, mechanisms of sensory processing and motor control.

essential logic' [180]. The focus of biomimicry is to advance human material interests; whereas biophilia focuses on a wider range of ways people are inherently inclined to attach meaning to and derive benefit from nature, and how this fosters human physical and mental wellbeing [180]. Beyond merely imitating form and structural properties of natural systems [424]; biomimicry has been extended to a potential paradigm to guide the development of social relationships and communities [180,424]. Expanding on relevant literature, Zhong et al.'s review of biophilic design in architecture and it's contributions on health & wellbeing [286] and sustainability [424] addresses the link between biophilia and environmental awareness in the buildings [424].

Nature is a great inspiration for shape and color changing interfaces; extended to Adaptive Architecture and Shape Changing interfaces research. Unpacking color and shape change mechanisms and how they relate to diverse natural processes further; *color change* (see figure 01) is a successful mechanism to communicate meaning between diverse natural organisms, achieved through biochemical reactions. An example from plants; in plants' leaves, color change is a chemical process whereby different coloring pigments are revealed due to changing environmental conditions[47]. Color change is not only a property of plants, but also animals. For instance, in jellyfish, color change is produced by pigment too. Color change in jellyfish can be an aging factor, dependent on food consumption or -in the case of bioluminescence- a mechanism to distract predators and attract potential mates. Bioluminescence is a chemical reaction involving light-emitting molecules and enzymes[48], and is observed in many living organisms at sea (from plankton to sharks) and land (fireflies, fungus). *Shape change*, such as the folding and unfolding of leaves or flowers is an indication of state change, transition between day and night, response to changing environmental conditions or a mechanism to avoid predators (camouflage), assist movement, or allow reproduction. Shape change in other organisms involves expansion or contraction of soft parts and aims to generate movement, noise, or assist with camouflage; examples are the movement of jellyfish or the expansion and contraction of soft parts of amphibians -e.g. frog's vocal sack. As these natural processes are interwoven with natural life and death cycles, we often intuitively associate and interpretate color and shape change properties with natural features, stages of life-cycle, and animal behavior. For instance, a green color is often positive and an indication of health, yellow and red are alarming or an indication of danger etc.

[47] As the sun exposure becomes less, chlorophyll (green pigment) production slows down, allowing the hidden orange and yellow pigments (carotenoids and xanthophylls) appear and fade at a much slower rate. The red pigment (anthocyanin) is also produced depending on the ratio of sunny days and cool nights. The brown pigment (tannin) is the last to break down in a leaf before it falls. https://extension.usu.edu/archive/what-causes-leaves-to-change-color

[48] https://www.amnh.org/explore/videos/oceans/jellies-down-deep/how-the-jelly-got-its-glow

Figure 15: Color change in leaves

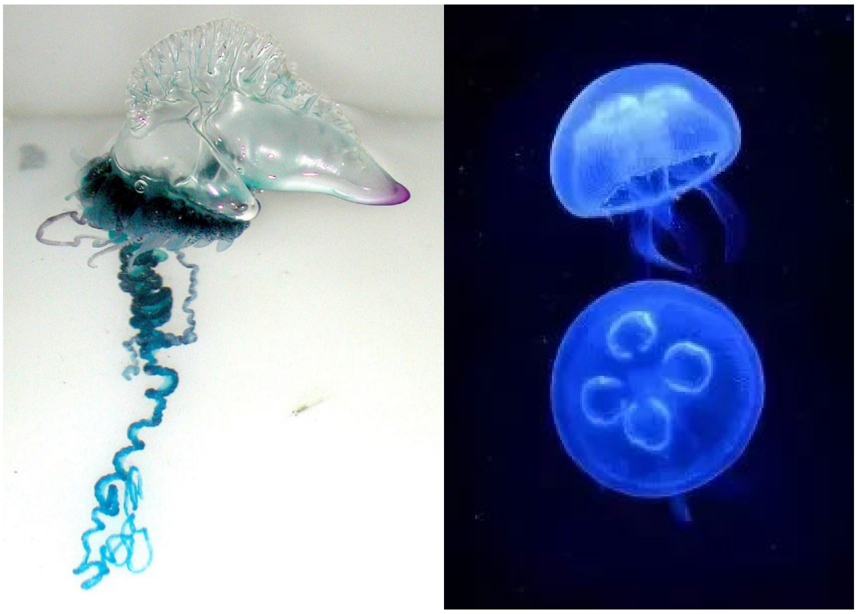

Figure 16: Color change and organic movement seen in Portuguese man o’ war and moon jellyfish as a source of inspiration for biomimetic feedback.

These principles of shape and color change in nature have inspired researchers when designing shape changing systems. The work of Qamar et al. (see Morphino)[303] focuses on bioinspired design of shape change; developing a card-based tool to enable design of future interfaces. Qamar et al categorizes existing soft actuating mechanisms to elastomers, auxetics, rollable, foldable, anisotropic, inflatable, multi-stable and shape memory; providing an extensive overview of how these mechanisms are visible in nature across different living organisms [303].

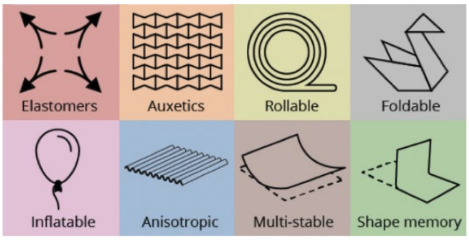

Figure 2. Mechanisms of shape-change from the *MorphUI* database [87]

Organism	Categories	Organism	Categories	Organism	Categories
Human skin	Elastomers, Auxetics, Shape memory	Bat wings	Foldable, Anisotropic	Sea cucumber	Elastomers, Inflatable, Shape memory
Flea legs	Elastomers, Multi-stable	Peacock train	Foldable	Starfish	Elastomers, Inflatable, Shape memory
Mollusc hinge	Elastomers, Foldable, Multi-stable	Hornbeam leaf	Auxetics, Foldable	Octopus arms	Elastomers, Rollable, Inflatable, Shape memory
Spider silk	Elastomers, Auxetics	Ice plant	Foldable, Anisotropic, Shape memory	Cuttlefish skin	Inflatable, Foldable
Cow udder	Auxetics	Pine cone	Foldable, Anisotropic, Shape memory	Venus flytrap	Foldable, Multi-stable
Porcupinefish	Elastomers, Inflatable	Tree branches	Anisotropic	Bladderwort	Multi-stable
Female cane toad	Inflatable	Three-banded armadillo	Rollable	Bittercress siliques	Rollable, Multi-stable
Frigatebird	Inflatable	Golden wheel spider	Rollable	Wheat awns	Anisotropic, Shape memory
Walrus	Inflatable	Mother-of-pearl moth caterpillar	Rollable	Sensitive plant	Foldable, Anisotropic, Shape memory
Ladybird wings	Foldable	Butterfly proboscis	Rollable, Multi-stable	Cucumber tendril	Rollable, Shape memory

Table 1. Morphino cards generated, linked to the respective categories from the *MorphUI* database [87]

Figure 17: Morphino shape change taxonomies and cards [306]

Beyond color, form and shape change imitation [180,213,286] relevant research in adaptive architecture explores biomimetic design in the large scale through the use of innovative actuating materials. Utilizing soft robotics & actuating materials agenda [36,328]; examples include pneumatic façade skins and use of SMA on interior elements [10,37,131,189]. Many works engage with biophilia & biomimicry with a view to advance technology in Adaptive Architecture and Building Skins in response to climate change - see for instance bio-materials [398] and hygroscopic materials for passive responsive building skins [309]. In the smaller scale, the use of actuating textiles [34,242,289], pneumatics and soft actuators has manifested in works such as ActuEater [240] or Auto-Inflatables [289]; contributing to aspects of biophilic design in architectural furniture and interiors [43,157,325]. A relevant example is NatureBot [225], a robotic shape-changing installation mediating a sense of immersive connection to nature; designed based on Attention Restoration Theory (ART) [225] and addressing aspects of biomimicry & biophilia, and swarm robotics.

Soft robotics and actuating materials' research [12,36,328,408] is an emerging agenda within HCI design research that engages with robotic systems and metamaterials that imitate living tissues heavily influenced by biomimicry and biophilia [128,286,371,424]; extended to the design research on shape and color-changing displays and adaptive architectures [303]. Examples of soft robotic displays include works using Smart Memory Alloy (SMA) actuators [49,71,240], pneumatic interfaces [237,381,384] and inflatable artifacts [37,157,360]. Reports on soft sensor-actuator systems include studies on haptics and tangible interaction

[113,241,250,342]. Soft robotics often address modularity[49] [77,272,408,415]; expanding the design field of modular shape changing displays [237,250], providing enhanced opportunities for user customizability [77,272,408], addressing aspects of physical scale and dimensionality of feedback in the buildings [325,360] and creating opportunities for swarm robotic behaviors [275,333].

The following subsection dives into the characteristics of soft robotics & actuated materials agenda; and maps their application in architecture & adaptive architecture and interior/ interactive design.

2.2.2.3. Soft Robotics & actuated materials overview

Soft robotics and actuated (composite) materials is a currently expanding field with increasing relevance and interest to the field of HBI research; involving the use of programmable and actuated materials at different scales and fields of application (i.e. from wearables and health, to climate adaptive architecture). Soft robotics employ soft, flexible materials with elastic actuation mechanisms (see hydraulic actuators or SMA for instance) to build systems that are adaptable and compliant; creating novel experiences and interfaces. Schmitt et al.'s [328] review on soft robotics highlights the emerging trend of adopting more flexible systems in robotics- e.g., serial elastic actuators – to enhance safety and user-interaction potentials, contributing to the emergence of new mechanisms.

It is hard to establish exactly what soft robotic and actuated materials research in HCI consists of; as there are plenty of works using different terms, approaches and materials, and for different purposes – actuated materials, soft actuators, shape-changing interfaces, pneumatics to name a few [36,321,328]. Brocker et al.[36] address this polyphony while they attempt to map the landscape of current soft robotics research in HCI; focusing on current challenges and propose solutions for resources accessibility and directions for future growth in the HCI research community[50].

There is an inherent concern on materiality and biomimicry [180,213] or bio-inspiration in soft robotics and actuated materials research [371,416]. Soft robotics research gets inspiration from natural processes and properties, while finding innovative ways to recreate them [371,416]. Soft robotic systems are built from flexible materials, simulating mechanical and structural properties similar to those of living tissues [323,371]. To imitate natural tissues; composite materials and innovative geometrical arrangements are employed; see for instance origami mechanisms [178,273,280] in shape-changing interfaces[51] and auxetic materials[52]– for instance, see broader research from Alexandra Ion[53] [164,165] or the work of Chuck Hoberman (Figure 18).

[49] Modularity is a way of decomposing a big and complex system or product into small, simple, independent, and manageable modular units that can be easily composed, decomposed, and replaced, which can be frequently found in both nature or industrial systems [415].
[50] https://www.softrobotics.io/chi22
[51] For instance, see applications in aerospace engineering https://www.youtube.com/watch?v=jjt2lOjMdJ0
[52] For instance, see KinetiX by MIT lab https://www.youtube.com/watch?v=XP5Fk-lHvK0
[53] https://interactive-structures.org/

Figure 18: Chuck Hoberman's auxetic adaptive architecture structures.

Soft robotics and actuated materials involve research on and use of electronic and 3D textiles, Shape Memory Alloy (SMA) wires, silicone and other elastomers - such as fluidic, hydraulic and electrohydraulic actuators [300,328]. An extensive review on soft robotics manufacturing parts is provided by Schmitt et al [328]. Purnendu et al [300] provide a short but comprehensive view of soft fluidic actuators and their pros and cons, while exhibiting the potentials of their electrohydraulic actuators [301]. Briefly, they mention the use of hygromorphic materials and hydrogels - see Transformative appetite[54]. A common strategy is using heat to activate shape change in composite materials - for instance using thermobimetals, thermoplastic elastomers such as Shape Memory Polymers[55] [93], or the more widely used combination of Shape Memory Alloy (SMA) wire with fabrics. The latter generates mechanical force by coupling two materials with differential expansion rates under various stimuli; for instance see projects such as the Printed Paper Actuator [379] (see Figure 23), Thermorph[56] and Seamless Seams by Nabil et al. [245] (see Figure 22).

SMA wire [240] is light, compact and silent in operation, but has slow and often imprecise response time. Pneumatics [403] offer an alternative method for prototyping bioinspired shape-changing interfaces. Pneumatic actuators require an external fluid source for inflation and deflation depending on their function - see for instance FlowIO platform[57] and Auxetic Breath [407] - and use of tubing, pumps and valves; which limits their speed, adds noise, and hinders portability. Pumping alternatives such as chemical reactions have been explored for pneumatic inflation; for instance, PITAS [60] is a composite layered material made out of conductive silicone which changes shape and color when electricity goes through. Similar to pneumatics,

[54] https://tangible.media.mit.edu/project/transformative-appetite/

[55] See Breathing façade, combining auxetics with shape memory polymers https://www.youtube.com/watch?v=Syn7TaX90Ik, and research on 3D printed Shape Memory Polymers https://www.youtube.com/watch?v=4JuHBtquP1I

[56] https://www.morphingmatter.cs.cmu.edu/projects/thermorph

[57] https://www.softrobotics.io/

actuators which use liquids as working fluids have also been proposed to eliminate pumping noise, such as hydraulic actuators [301]– see milliMorph [205]- planar actuators [259] or phase-change actuators [128]; still these examples are still slow in response time. A silent and rapid actuating technology recently explored for prototyping bioinspired shape-changing interfaces are Dielectric Elastomer Actuators (DEA)[116,117,301,401]. DEAs are activated by electrostatic voltage, are rapid and silent in actuation. They have been explored for applications in the domain of haptics, handheld shape-changing devices and responsive environments [117,118]; but they are limited in availability due to their high cost of the material and specific know-how of fabrication [116]. Recent textile advancements can also be categorized as an upcoming part of soft robotics research – see 3D textiles and spacer textiles for instance [12,13].

There is a new generation of researchers & designers that emphasize in soft robotics and actuated materials accessibility, the open-source distribution of how-to create soft robots, and the use of low-cost materials and relatively accessible ways to manufacture them – for instance, see Soft Robotics Toolkit[58] by Harvard Biodesign Lab. A pioneer in open-source soft electronics and actuators is Jie Qi[59] with the well-known project 'flapping crane'[60] using origami and SMA wires, or the folding paper example. The online community Instructables [61] also provides a great space for accessible manufacturing of soft robotics.

Beyond their functional and mechanical properties, soft robotics and actuated materials research has many areas of application [328]. Most common areas are wearables [107,368], haptics [64,188], hand-held devices [237,403], but recently also in architecture and interior design [189,325,381,383]. As the specific research focus of this PhD work is Human-Building Interaction research, and therefore, the interactions in and with the buildings; I will explicitly focus on applications of soft robotics to create experiences and interfaces in the buildings briefly discussing relevant architecture and interior design research.

2.3.3.1. Soft Robotics and actuated materials in Architecture

Robotics applications in architectural scale have many manifestations [189,404]. Architects have used a variety of terms to describe projects that often employ robotics principles and techniques in physical scale in the buildings; see kinetic, interactive, responsive, or adaptive architecture for instance [189,404]; although these terms better describe the spatial experience that the architects' want to achieve and can often include rigid robotic, soft robotic and non-robotic elements. Nabil et al [246] also addresses the desired experience of some interactive architecture's when addressing Organic User Interfaces (OUIs): flexible, actuated

[58] https://softroboticstoolkit.com/home
[59] https://www.exploratorium.edu/tinkering/tinkerers/jie-qi, https://makezine.com/article/craft/skill-builder-working-with-shape-memory-alloy/ , http://highlowtech.org/?p=1448
[60] https://www.youtube.com/watch?v=Kjf69xAMGGI, https://www.youtube.com/@qijies/videos, and https://fab.cba.mit.edu/classes/863.10/people/jie.qi/
[61] https://www.instructables.com/Soft-Robotic-Gripper/ and https://www.instructables.com/Air-Powered-Soft-Robotic-Gripper/

interfaces characterized by being aesthetically pleasing, intuitively manipulated and ubiquitously *embedded in our daily life;* partially engaging with soft robotics research in architecture.

Robotics in architecture are used to automate building construction [426]; applications related with off-site prefabrication, on-site fabrication & exoskeletons- and building operation -drones & autonomous vehicles for building inspection and evaluation- as well as building function - see adaptive façade elements, foldable roofs or wall partitions [169,374,404]. Adaptive facades are potentially the most common robotic applications; examples such as Al Bahr Towers[62] by Aedas Architects, Abu Dhabi 2012 or Kinetower booming façade or Cafe-restaurant OPEN, Amsterdam by de Architekten Cie[63]. Many of adaptive facade projects aim to passively adapt to environmental conditions [413] – such as daylight[64]– using both rigid and soft approaches to robotics. San Francisco's Randall Museum façade by Charles Showers or Brisbane airport façade by Ned kahn and Hassel are examples of a passive approach to adaptive facades; using the wind to create a coordinated movement effect between independent metal elements.

Figure 19: Media-Tic building and the use of pneumatics (EFTE) in large scale.

The reality is that the scale and nature of architectural construction poses constraints in the application of soft robotics; achieving safety, construction stability and robustness at scale often necessitates that more rigid or mixed approaches to robotics are employed. Still, with research on soft-robotics and actuated composite materials currently expanding; past difficulties such as the training of shape-memory materials, or material robustness are now addressed through new passive composite materials, giving ground to soft robotic approaches for large scale building applications. In architectural practice, the most promising applications

[62] https://parametrichouse.com/adaptive-facades1/
[63] https://weburbanist.com/2015/03/11/adaptive-architecture-12-transforming-breathing-buildings/2/
[64] https://surfacesreporter.com/articles/123164/adaptable-daylight-systems-and-benefits-architecture-projects-with-dynamic-facades-sr-exclusive

for soft robotics are façade systems [413] – e.g. see pneumatic facades[65] and soft adaptive skins[66] – and interior structural elements of the building – i.e. wall partitions, floors; and the combination of passive composite materials (climate-responsive materials)[67] and soft robotics technologies (soft skin actuators).

Advancements can be seen in pavilions or installations[68] which are often used as 'prototypes' of using a novel technology and achieving a unique spatial experience; illustrating a 'possible future' to be scaled up to a bigger construction. Some examples of such works are the Capacitor[69] by John Grade, Parametric Space[70] by Zaha Hadid, the Cerebral Hut[71] or the Exobuilding [330]- illustrating examples of soft robotics applied in adaptive skins and unique data-driven responses of architecture. Some of these projects replicate design patterns of existing robotic kinetic façades to a 'soft' alternative – see Kelly Zona's façade[72] prototype with Smart Memory Alloy (SMA) wires or Hiroya Tanaka's[73] Auxedic façade with Smart Memory Polymer (SMP).

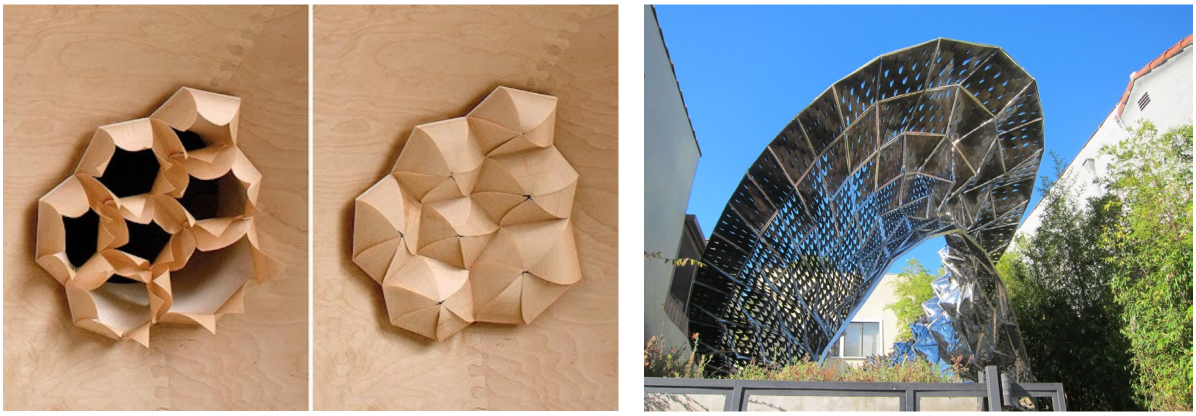

Figure 20: Hygroskin [309] on the left, and Sung's work [358] on thermobimetals on the right.

Passive Climate-adaptive buildings[74] [413]– those that utilizing passive composite material[75] properties to respond through shape or color change to environmental conditions - is one of the most promising research areas of soft-robotics in architecture. They do not require electronic or mechanical control; reducing energy-consumption of adaptive buildings. For instance, thermobimetals[76] (composite materials consisting of metals with differential expansion rates under heat, resulting to changing their curvature when heated) are of great

65 http://andrzejzarzycki.com/pneumatic-facade/
66 https://surfacesreporter.com/articles/10286/breathing-skin and https://www.iaacblog.com/programs/soft-skin/
67 https://www.re-thinkingthefuture.com/rtf-fresh-perspectives/a1231-smart-materials-the-future-of-architecture/
68 https://www.vice.com/en/article/yp5z8w/exclusive-video-doris-sungs-living-architecture
69 https://www.designboom.com/art/john-grades-capacitor-moves-and-illuminates-with-weather-data/
70 https://www.dezeen.com/2013/07/03/parametric-space-by-zaha-hadid-architects/
71 http://www.ozeloffice.com/cerebral-hut
72 https://vimeo.com/110907142
73 https://www.youtube.com/watch?v=Syn7TaX90lk
74 https://www.youtube.com/watch?v=6XPzQgOH3pE
75 https://www.re-thinkingthefuture.com/rtf-fresh-perspectives/a1231-smart-materials-the-future-of-architecture/
76 https://materiability.com/portfolio/thermobimetals/

interest for passive shape change in architecture; thermochromic materials [2] change color when temperature rises being very interesting for applications such as smart windows or large-scale printing. The work of Doris Sung [358] (Figure 20) shows the potentials of thermobimetals in façade construction. Expanding the discussion on metal heat-responsive actuators, Smart Memory Alloy [240] such as Nitinol[77] can also be used to create passive climate-adaptive architectures especially in warm countries [49] as the energy to heat them can partially or fully be generated by environmental conditions[78]. Beyond Nitinol, there are more composite materials that can be utilized to create passive – i.e. no power supply needed- adaptation. Apart from heat-responsive, there are composite construction materials that respond to water percentage in the atmosphere – i.e. humidity and moisture (hygromorphic and hydromorphic materials), see projects from A. Menges and S.Reichert [309] such as Hygroskin[79] and HygroScope[80] (Figure 20) made of wood-composite material that is physically programmed to respond to fluctuations to humidity through shape-change . Finally, photochromic[81] materials respond by changing color when exposed to light - see Lumina [184] and PhotoChromeleon[82] by MIT; or even cleaning air based on chemical reactions with sunlight[83].

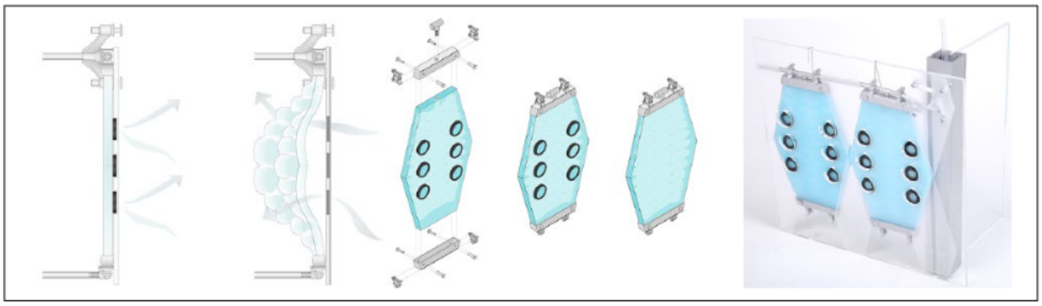

Figure 3. **The Soft Magnetic Façade with thermochromic pneumatic components.**
The assembly developed by Ernessa Francois, Olivia Szymkowski, and Natalia Wilk, NJIT'19.

Figure 20: Francois et al.'s prototype of soft magnetic skin with thermochromic pneumatic components.

Pneumatic systems [111,131,214] are potentially the most common applications of soft robotics in architecture. From inflatable polythene to ETFE cushions, there are many examples of pneumatic roofs or pneumatic façades/building skins. ETFE (ethylene tetra fluoro-ethylene - ETFE) is a polymer source material used recently brought into the construction industry by the architect Ben Morris; used in the form of air-filled cushions [131]. ETFE is mostly (if not exclusively) used as multi-layered inflated cushion skin with low air pressure. The layering of

[77] Nickel titanium, also known as Nitinol, is a metal alloy of nickel and titanium, where the two elements are present in roughly equal atomic percentages. Different alloys are named according to the weight percentage of nickel; e.g., Nitinol 55 and Nitinol 60. It exhibits the shape memory effect and superelasticity at different temperatures.
[78] https://materiability.com/portfolio/self-adaptive-membrane/
[79] https://www.vice.com/en/article/aenwp5/hygroskin-scultpure-installation-mimics-real-skin
[80] http://www.achimmenges.net/?p=5083
[81] https://www.olikrom.com/en/blog-olikrom/the-expert-eye/all-about-photochromic-materials/
[82] https://hcie.csail.mit.edu/research/photochromeleon/photochromeleon.html
[83] https://www.smithsonianmag.com/innovation/smog-eating-buildings-battle-air-pollution-180954781/

the cushion can create active (deployable) internal surfaces for controllable opacity or responsive thermal performance. ETFE air-filled cushions are used in big roof and cladding projects, replacing glass at a fraction of the weight and with attendant structural capacity. ETFE cushions are often connected to a pneumatic air-pumping system, which regulates their behaviour depending on environmental stresses (temperature, air humidity and pressure atmospheric) - swelling and deflating them when necessary. An example of ETFE pneumatic panels use is the Media-Tic building in Barcelona [214] (Figure 19), which, being able to be injected by air and nitrogen, becomes inflated or deflated according to the external environmental conditions- i.e. cushions keep swollen in cold periods to exploit the thermal resistance of the air, and deflate the rest of the year when temperatures rise. A different approach comes from Tobias Becker and his 'Breathing Skin'[84]; whereby pneumatic muscles are assisting with air circulation through porosities; or Francois et al.'s prototype of soft magnetic skin[85] with thermochromic pneumatic components.

Other materials used to develop pneumatics are PVC, Fiberclass and other types of polymers, such as silicone[131]. At smaller scale – i.e. interiors, wall partitions etc. – polypropylene and polythene[86] such as silicone, PLA and vinyl are widely used [131].

2.3.3.2. Soft robotics & actuated materials for interactive interiors

Beyond facades and roofs, research in architectural interiors is currently opening for soft robotics. The scale allows for a wider range of applications of soft robotics [321]; utilizing a greater range of materials and actuators [302]. For instance, see examples of soft robotic interactive ceilings such as PolySurface [103]; research in fluidic [128,205], electroactive [116], electrohydraulic [300] and hydroactive polymers [118] illustrated through room [103] and ceiling installations [117] ; soft robotic walls that provide biofeedback - see LivingSurface [409]; or soft actuating materials – see Lumina [184]. Many projects utilize SMAs to make soft robotic room dividers – see Shutters [71]- and a soft-robotic tablecloth and other interactive artifacts for interiors – see actuEater [240], Seamless Seams [245]. Nabil's work on interactive interiors illustrates some very interesting attempts to design and speculate around the space and application of soft robotics and e-textiles -see projects such as Decoraction [242] or Interioractive [244] (Figure 22). Nabil's work is very linked with fabrics, a highly promising area for soft robotics for interior design and beyond – see wearable soft robotics [288]. Recently, 3D and space fabrics have also been invented [113]– see work by Albaugh et al. [12,13] – widening the space of soft actuating materials with robotic capacities for interior architecture research.

[84] https://surfacesreporter.com/articles/10286/breathing-skin
[85] http://andrzejzarzycki.com/pneumatic-facade/
[86] https://www.media.mit.edu/projects/therms-up/overview/

Figure 212: The use of SMA wires for architectural interior, illustrated in Shutters[71] and ActuEater[240].

Pneumatics and inflatables are again dominating interior architecture soft robotics [361,383,403]. Projects such as aeroMorph [279] (Figure 23), PrintInflatables [325], Reflatables [239] and BlowFab [400] explore low-cost and scalable workarounds for room-scale inflatable 3D printing, design & deployment; Therms-Up[65] utilizes existing wasted thermoplastic bags. Project such as LiftTiles [360] combines rigid materials with soft actuators to create a modular adaptive floor; transferring Ishii's and Leithinger's radical atoms [166] to a big scale and into the world of adaptive interiors/furniture. The material flexibility gives room for light-weight interventions – see Sticky actuator [379] (Figure 23) or Electriflow [301] and their potentials for creating interactive wallpapers and animating other interior light-weight objects [304]; or sticky actuator [259] – a lightweight add-on to animate everyday objects. The noise often generated by pumps that enable pneumatic systems [339] is a problem space for building interior's applications [166,259]; but recent projects such as PITAS [60] or Auto-inflatables [384] show promising ground in developing alternative methods to inflate pneumatics.

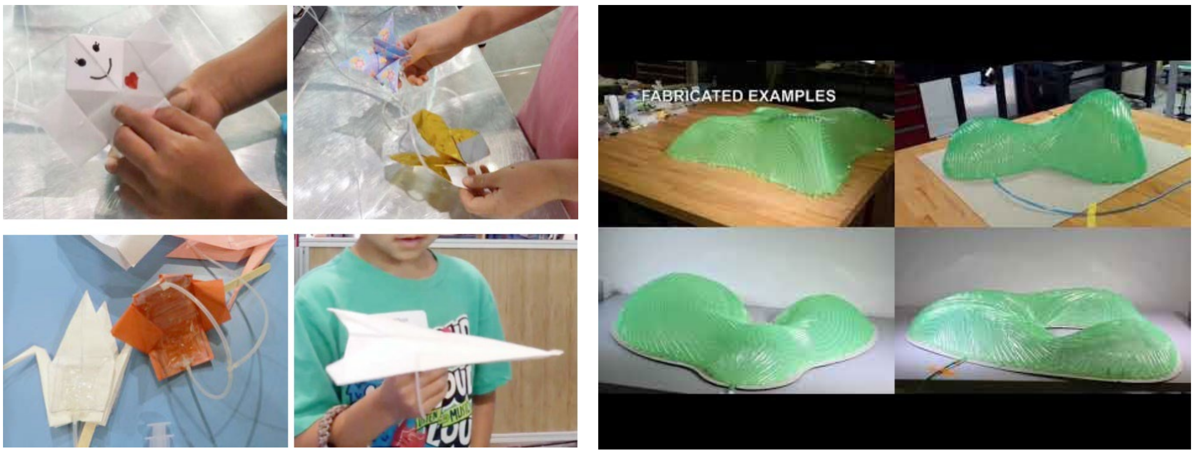

Figure 22: Examples of the use of pneumatics for actuators and shape-changing interfaces. On the left, the Sticky actuator [379], on the right, aeroMorph project [279].

Nature (biomimicry) is a unique source of inspiration for the world of soft robotics in interior design [303,322,397]. Origami-inspired shape-changing actuators [178,273,280,300,416] and furniture have a great research interest and potential for interior architecture -see projects such as Tessella [59]or work by trex-lab[87]. Auxetic-inspired structures and metamaterials are also gaining ground, with many interesting application areas – see KinetiX by MIT lab [278]. Other projects that support modularity to create user-customizable applications and furniture [272,276]. 3D printing using soft polymers [186,273,383] (such as silicone and PLA) and workarounds that combine printing and cutting different materials for the creation of 3D printed inflatables [144] is a space that opens in research for soft robotic interiors [135]. More recently, 4D printing [355,380] – i.e. the 3D printing of shape memory polymers[94] –has great potentials for soft robotic interior architectures - see projects such as Protochair [93] and self-healing UI [252].

Finally, some broader works in data physicalization relevant to soft robotics agenda are works in slow HCI – see Laina [226], or the work of Odom et al. [265,267]. Although not directly linked with the soft-robotics; slow HCI addresses how physical properties can contribute to data awareness over time [140,266], drawing parallels with how information and change manifests itself in nature [286,424]. This has increased relevance with the temporal dimension of soft robotics' displays - given soft actuations are often slow [416] and with biomimicry is in the core of this agenda[371] - contributing to rethinking of data physicalizations utilizing soft material actuations in different temporal and physical scales in the buildings.

Summarizing, there is a push towards soft robotics artifacts for environmental awareness [104,411]. Years after Shutters [71], there is a revived interest in the experience of climate in the buildings – see atmospheric interfaces [40,41]; motivated by pressing challenges of COVID-19 and prominent research gaps in the experience of air quality in the buildings and its impact on wellbeing **(RQ2).** Ambient feedback can be re-framed under the soft-robotics agenda, seeing architectural interiors as a novel space of application for creating data awareness and enhancing the quality of life and wellbeing of their residents. Shutters [71] has been a groundbreaking project; being one of the first that brought the use of soft robotics (SMA wires) to architectural interior elements for the purpose of data and environmental awareness on air quality in the workplace. In Shutters, the architectural scale creates unique potentials for ambient feedback, as the actuation and the physical positioning of the artifacts in space utilizes natural light and communicates information. Shutters is a key inspirational project for this PhD work; pointing towards design research around soft robotic room dividers that provide ambient environmental feedback **(RQ3).**

There are prominent research gaps in the design and use of soft robotics as displays (and particularly climatic displays) in the scale of architecture and interior architecture. The architectural scale and its unique potential for ambient feedback through soft robotic actuations remains relatively unexplored; which is the key purpose of Design Research described in this work **(RQ3).** Beyond Shutters and the use of SMAs and textiles; pneumatics

[87] http://trexlab.com/

and inflatables are rarely used in the context of ambient or physical displays for climatic data and are further explored in this work **(RQ3).**

Finally, the user experience of soft robotics deployed the buildings has not been widely explored – see limited relevant research on the effect of pneumatic envelopes in the experiences of the occupants [208]; which could guide the human-centered design and development of pneumatic skins and structures deployed in buildings **(RQ1, RQ3).** Design research lacks comprehensive evaluation with regards the building occupant's experiences of and around inflatables in architectural interiors [157]; particularly as environmental displays. Responding to the above design research gaps, Chapter 7 is concerned with the making of soft robotic interventions with the purpose of using them as climatic displays in the workplace; while Chapter 8 is concerned with their evaluation **(RQ3).**

2.3. Summarizing research gaps for the quantified workplace that this PhD addresses (RQ1, RQ2, RQ3).

This section summarizes the key literature gaps addressed in the previous sections, and how this PhD positions itself towards them.

To address some of the challenges around the human experience in smart offices **(RQ1),** this PhD treats the problem from the ground-up, following an inductive (and not deductive) research approach. Correspondingly, the research questions emerged from the need to develop a holistic understanding of the human experiences in the context of quantification to then address key findings; rather than after a systematic literature review of the relevant works and the selective focus on specific aspects from the start – such as privacy, or air quality. Extending this, this work does not explicitly focus on solving the privacy paradox in smart offices; but explores the perceptions of privacy through mapping the broader experiences of the building occupants of a smart office building **(RQ1)** and through discussing the potential issues (and potential solutions) as they evolved throughout the discussions with building occupants – see Chapter 4.

Perceived privacy in smart office buildings remains a highly vague and complex matter in HBI, HCI and Ubicomp research [26,99,133,193,251,260,261], where lies one of the contributions of this PhD **(RQ1)**- e.g. **see Chapters 4,6**. The reality of lived-in smart office buildings has unresolved complexities with regards to their users' experiences, such as the feeling of control on their environments [231,232], and perceived and actual privacy [26,133,193,260]; whereby further research is meaningful. Mentioning relevant work, Nepal et al [255] have explored the benefits of use and privacy concerns on passive sensing in the workplace; unpacking that the lack of control over the sensor data collection was a significant privacy concern [255]. Other work includes research on changing perceptions on data in the workplace and privacy concerns [68,90,133]. However, most of these works do not consider the intersection of physical and digital dimension with regards to privacy perceptions (RQ1). Reflecting on present research gaps around privacy, the issue of data invisibility and lack of any control over when & where data is collected is one of the key problems in the workplace; which recent works attempt to address through various ways including tangible interfaces . The underlying issue stems from the perception territory, and the ability to control physical & digital boundaries; which is often not the case in smart offices. Some recent works attempt to address the issue of territory – see WaddleWalls [275], a robotic room divider for customizing visual privacy at the workplace. Yet more research is needed on understanding the impact of physical space on perceptions of privacy in smart buildings **(RQ1)**; to guide the design of interventions that bring the physical and the digital/data dimensions together and in ways that can be customizable by occupants **(RQ3).** This PhD contributes to these research gaps primarily in Chapter 4 & Chapter 6.

Relevant to privacy perceptions, data awareness in smart buildings is a key challenge for HBI researchers **(RQ1, RQ3).** Past works address this through diverse design interventions – i.e. awareness interfaces [45,156,187,299]. Reflecting on relevant works, researchers have deployed a variety of technologies and artifacts to surface data in office buildings to create awareness and engagement with those data– i.e. physical displays or ambient displays often embedded in the building's existing infrastructure [10,148,156,335,378,394]. A relevant example is Yvonne Rogers' work [315] on data displays for employees' sedentary behavior; exploring different ambient and physical displays including lights, screens and pendants as physical displays to communicate physical activity data and the impact on employees' behavior [315]. Achieving data awareness and engagement with data collection practices in lived-in smart buildings remains another open challenge, where lies a key contribution of this PhD **(RQ1, RQ3)** -see Chapters 4, 6, 7, 8. This work approaches the issue of awareness and engagement through creating modular and customizable physical interventions; aiming to surface environmental data to create an holistic experience around them – an experience that includes shape, color, noise changes and can be further modified by the building occupants as they think best.

Additionally, research on design for wellbeing in smart office buildings is a field rapidly evolving [145,187,228]. Briefly reflecting on relevant research, past work has focused on environmental wellbeing, enhancing the experience of microclimate in smart workplace buildings as well as the productivity of employees [10,70,74,216]. Physical comfort is a key relevant term throughout literature, with studies addressing multiple aspects of the perceived indoor climate and developing technologies to support the environmental wellbeing of the building occupants through technologies that facilitate climate data collection and awareness [10,70,74,83,422]. As an example, recent studies look at the impact of air quality notifications on wellbeing and the collective behavior in office spaces [187,344,422,423]. Other works have accomplished an understanding of how the design of the built environment impacts wellbeing and social interactions [9,42]. Researchers have employed different technologies to unpack relationships between group behavior and physical environments, through passive & active sensing [9,42,377], to illustrate how the physical design of workplaces supports or inhibits specific types of interactions, how different behavioral profiles thrive in specific spatial configurations [9,377]. In this work and opposed to many of these past examples, buidling occupants are treated as key players into shaping the physical, digital and environmental parameters of their offices facilitated to do so through a data awareness intervention – see Chapter 8 **(RQ3).** Although the focus of the intervention is air quality awareness (contributing to limited research in this aspect in the first place); the design and the conception of the intervention addresses multiple dimensions of wellbeing, such as the feeling of control over the physical space, and the ability to customize it (individually and collectively)- see Chapter 8 **(RQ1, RQ2, RQ3).** The intervention extends the scope of Shutters [71] (see relevant design exploration on Chapter 7) by rethinking form factors through a customizable and modular lense; similarly diverging from recent relevant literature – see Hilowear[422].

Finally, altough past research on integrated wellbeing [353] has somewhat informed contemporary building design practice– see WELL[88] and LEED[89] certificates as well as the development of diverse IoT technology to communicate and collectively manage data for wellbeing in offices [10,16,70,90,171,349] - the dimensions of the physical design and data integration do not meet as much as much they should (within smart/quantified office buildings and for wellbeing purposes). This is another contribution of this PhD, as it explores the space inbetween the building layers of the data and the physical experience in the buildings (in the context of wellbeing), creating design tools to navigate this space with the building occupants (see card kit in Chapter 6) **(RQ2, RQ3)** and drive research based on their insights.

Summarizing, aiming to address the research gaps around the human experience of lived-in smart buildings **(RQ1),** this work unpacks the occupants' experiences of a smart office building and their perceptions around data collection and use for health and wellbeing **(RQ2).** Moreover, responding to the research challenges of integrating physical design, data and materiality in smart buildings in the context of wellbeing, and the developing building-integrated technology that empowers building occupants to gain awareness (of data collection) and shape their environments (in terms of the microclimate, physical space, and considering privacy concerns), this work contributes with designing and evaluating a relevant intervention (ActuAir) **(RQ3).** All these considerations will be further discussed in the individual empirical chapters of this work.

The following section further unpacks the key methodological approaches and the rationale behind the choice of methods. Specific clarifications relevant with how the studies relate to each other, methods transparency and replicability are made, to support the scalability of findings.

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[88] https://www.wellcertified.com/

[89] https://www.usgbc.org/leed

Chapter 3. Methodology

The following sections provide an in-depth overview of key methodological concepts that this PhD is based upon (Section 3.1) and expand on methods employed and how they fit within the broader scope of the research activities (Section 3.2). Mixed Methods research is further discussed in Section 3.3. Design Research methods employed throughout this PhD including Design Fiction, Co-design, and Prototyping are discussed in detail in Section 3.4.

3.1. Key Methodological Concepts: Pragmatism, Mixed Methods & Design Research

Methodologically, this PhD aligns with a Pragmatist orientation to research [179]; an approach to doing research through acting [129]. Pragmatism, as a research paradigm, accepts multiple realities that are open to empirical inquiry [179]; rejecting the philosophical dualisms of the Objectivity (i.e. Hypothesis-Driven Research, Post-positivism, Quantitative methods) and Subjectivity (i.e. Exploratory Research, Constructivism, Qualitative methods). This allows the researcher to combine methods that fit in both Post-positivism and Constructivism inquiry [179], using abductive reasoning – hence often guiding the employment of a Mixed Methods approach, combining both Quantitative and Qualitative data analysis.

Pragmatism orients the researcher toward solving practical problems in the real world, used as a method of inquiry for the practical-minded [129]. For this reason, it also embraces Design Research [129]. For pragmatists, a sense of Reality is grounded in the environment and can only be encountered through human experience[90]; design research resonates with this philosophical orientation as it can involve knowledge generation through making and interacting with artifacts [129]. Essential in Design Research practice is to consider the introduction of new artefacts as responses to problems and needs in human activities. A new type of artifact is considered as a solution to a perceived problem. The knowledge obtained through making it and observing the human experiences around it can help reframe the initial problem/research question [129].

As a methodological approach, Pragmatism fits with HCI and particularly HBI research, a multidisciplinary action-based research field [142]. As HBI addresses human experiences and relationships with data in the built environment [143]; many related works employ Design Research, building and deploying artifacts in the buildings to explore human-data-environments relationships – see for instance work by Schnadelbach et al. [331] - and Mixed

[90] Design research resonates with the philosophical orientation of Pragmatism as it can involve knowledge generation through making and interacting with artifacts. Essential in Design Research practice is to consider the introduction of new artefacts as responses to problems and needs in human activities. A new type of artifact is considered as a solution to a perceived problem. The knowledge obtained through making it and observing the human experiences around it can help reframe the initial problem/research question. In that sense, Design Research and Pragmatism are not only concerned with "what-is", but there is also a knowledge orientation to a world that might become ("to-be"). A pragmatist and design researcher intervenes into the future with the purpose to construct a better world through making and installing artifacts; not only guessing or proposing what might be, but he/she also tries to install it through action [129].

Methods research, utilizing sensing technologies to collect and analyze data on human behavior in the buildings– see work by Alavi et.al [9] – or utilizing data-feedback strategies to explore aspects of behavior in the buildings, combining Design Research & Mixed Methods – see work by Alavi et.al [10,422]. The above works illustrate the different approaches in doing research in HBI field; albeit different, they fit under a Pragmatist lens.

Pragmatism allows for flexibility and diversity in the methods chosen to address given study purpose, context and research questions [129]. Similarly with many HBI research projects, this PhD employes both a Mixed Methods approach and Design Research to address the RQs, Aims and Objectives above; with both approaches considered as Empirical Research [129]. There is an intentional overlap between different methodological approaches – i.e. mixed methods and design research - to produce empirical findings. For instance, methods such as Co-Design and Design Fiction are employed for data collection (see Chapters 4 and 6) together with analyzing sensory and diary data (Chapter 5); the design of artifacts (Chapter 7) is evaluated through qualitative data collection and mixed methods analysis (Chapter 8).

The presentation of the Empirical Findings from this research is organized around two Sections (B & C) which both combine elements of Design Research and Mixed Methods (predominantly qualitative) analysis:

- *Section B. Understanding People in Place* consists of 3 Chapters. Section B is my account of the empirical research that focuses on understanding people's experiences in the quantified workplace; in the physical context of the office building (Chapter 4), the domestic office (Chapter 5) , and in both (hybrid) (Chapter 6). Mixed Methods have been employed in Chapter 5, as the focus of this chapter was on understanding aspects of the domestic workplace over time. Chapters 4 & 5 analyze predominantly qualitative data around occupants' perceptions and concerns; design research was also used to facilitate data collection in Chapter 4 (Design Fiction) and Chapter 6 (Co-Design).
- *Section C. Understanding Materiality: Design & Material explorations* consists of 2 chapters: Chapter 7 is the making of ActuAir prototype (Design Research), and Chapter 8 is ActuAir's empirical evaluation in the workplace (Qualitative research facilitated by the prototype's in-situ installation). The focus of this section is on materiality; on building an intervention as a respond to past findings and an understanding of the building occupants' perceptions and interpretations of this intervention in the workplace.

Sections B & C naturally differ with regards to the underlying approach driving data collection. In Section B, my interest was studying people in naturalistic context; and therefor I tried to be as little interventionist as possible. This extends to the choice of sensors used in each context. For example, in Chapter 4 which focuses on the smart building, the already installed industrial sensors and their data output is used in the studies to map participants' views; whereas in Chapter 5 which is about the domestic workplace, commodity wearable sensors were used as they are already widely accepted and used at home and the workplace. It is also important to note that the research focus in these Chapters was not on environmental data only; but the broader experience of quantification of and in the workplace; which further justifies the above sensory selections.

Roughly, the broader scope of the studies and the underlying approach driving research in Sections B & C follow a high-level design iteration framework as defined by Design Thinking[91] (see Figure 24). This design iteration has the following phases: Understand (human experiences); Define (the problem) Ideate (design solutions); Prototype (design and make an intervention as a response to the problem); Evaluate (the intervention). Section B concerns the Understand (Chapters 4 & 5) and Ideate (Chapters 6) phases; whereas Section C concerns the Prototype (Chapter 7) and Evaluate (Chapter 8) phases. Each chapters opens independent but intertwined design research spaces, suggests design implications and proposes directions for future design research as a response to the findings it discusses .

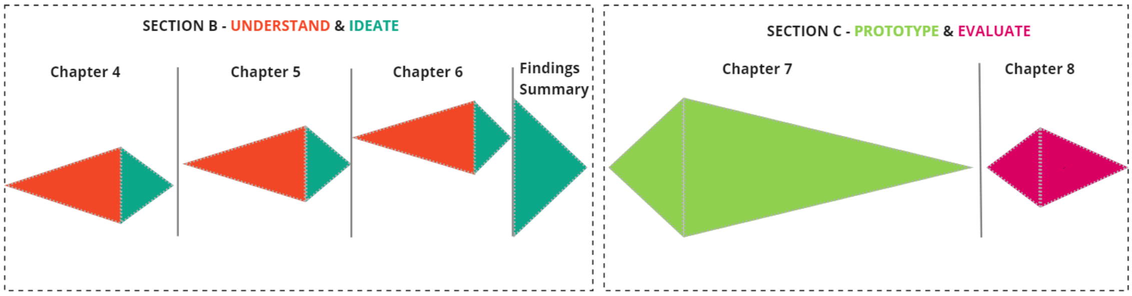

Figure 23: Thesis Empirical & Design Research Sections, their Chapters, and the high-level Design-Thinking process phases (Understand-Ideate-Prototype-Evaluate). The double diamond illustrates that each chapter widens the design space during the exploratory studies and then narrows down to design implications.

It is important to clarify that Chapters 4, 5 and 6 (Section B) respond to the research questions as independent entities – i.e. the studies of each do not respond to specific findings of the previous one. Chapter 6 validates findings from both Chapter 4 & 5, while providing an independent contribution. On the contrary, Chapters 7 and 8 (Section C) are practically (and chronologically) linked, with the output of the former (a prototype) used as input of the latter (evaluation studies). It is also highlighted that Section C does not intend to respond to all findings and design considerations as presented in Section B; but addresses some key selected findings and follows some key design considerations to develop and evaluate a prototype. With this PhD work being generative in nature; each chapter provides its own contributions while opening new opportunities for further research. Following this approach, Section C responds to key findings while framing new opportunities and challenges for design research.

[91] https://www.interaction-design.org/literature/article/5-stages-in-the-design-thinking-process

Pragmatism eschews an a-priori determination of all experimental variables to be tested [179]. Under the Pragmatism lens, this PhD was designed as a generative program of work that would organically evolve over time, adapting to unforeseen situations and changing circumstances - such as the move to remote data collection during COVID-19 lockdowns and the varying interests and engagement levels of the participants. In fact, the shift in the workplace imposed by COVID-19 was seen as a research challenge and research opportunity; adapting the research topic area to embrace these unforeseen changes.

Beyond COVID-19, this generative approach of doing research is central in this work; as specific themes and concepts observed in the findings gained importance over time and became a driving aspect over the course of this PhD, shifting the initial broader focus on quantification of; to air quality data experience in the workplace. To further explain this; the focus on wellbeing - on data for health and wellbeing in particular – was further strengthened because of COVID-19 impact. Furthermore, the association of air quality with wellbeing was an important finding in Chapter 5 which then further drove the focus around environmental wellbeing and data for air quality in the hybrid workplace (Chapter 6) and the design and evaluation of interventions that respond to environmental and air quality data (Chapters 7 & 8).

3.1.1. Mixed Methods Research

Mixed methods research broadly refers to the combination of qualitative and quantitative methods of data analysis within the same study or set of studies; and the production of intersubjective knowledge following abductive reasoning[92] [389,390,412]. Based on the methodological lens of Pragmatism, it rejects past rigid approaches of using either qualitative or quantitative data - acknowledging that in many ways they are inherently related[93] [230,390]. Pragmatism and mixed-methods research provide a theoretical ‘middle ground’ between

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[92] Mixed-methods research has emerged as the “third methodological movement” (Creswell & Plano Clark, 2007, p.13). As an important new research community, it involves research in which both qualitative and quantitative approaches to data gathering, analysis, interpretation, and presentation are used (Teddlie & Tashakkori, 2009, p. 7).

[93] Quantitative data are often based on qualitative judgments; and most of qualitative data can be described numerically – see Mayring Content Analysis [224].

postpositivism[94]and constructivism[95]; the theoretical bases for quantitative and qualitative research (Figure 25).

[94] Postpositivists see human experience as speculative and, therefore, not based on unchallengeable, rock-solid foundations. They argue that the external world exists independently of an individual's experience of it, and thus knowledge is not hypothetical and foundationless. They acknowledge that all research will be incomplete in one way or another, and they hold that approaches that can be tested and explored through the scientific method should be favored. This often results in the application of deductive approaches that rely on a series of steps to reach specific conclusions based on general premises. In general, quantitative research seeks generalizability through controlled, value-free (or value-neutral) processes that can test and validate theories through a process of falsification. The emphasis on falsification often leads quantitative researchers to focus on sample size and statistics to showcase broad generalizability. At its most shortsighted, some quantitative research considers the role of setting and context either irrelevant or unmanageable. A central critique is that some quantitative research models are statistics dependent, inflate the importance of mathematical averages, and cannot capture the complexity associated with human behavior. By focusing solely on numeric information, some approaches miss the depth and detail that are assigned to phenomena by participants themselves [390].

[95] Constructivists are skeptical of the idea of one universalistic notion of truth, they view meaningful understanding as contingent on human practices and thus different people's ability to socially construct reality in different ways. Although many qualitative researchers acknowledge the limitations inherent in reporting individual understandings of complex ideas and concepts, in their view research must do a better job in telling the stories of individuals. This often results in inductive approaches to research that rely on a series of steps to reach general conclusions based on specific premises. Qualitative research seeks to understand or make sense of the world based on how individuals experience and perceive it. Framed through social interaction and personal histories and narrative experiences, knowledge is inherently localized, and the notion of generalizability overly mythologized. Unlike quantitative researchers, qualitative researchers focus on the development of theories based on an interpretive or individualized process. Because there are many possible interpretations of the same data, however, qualitative researchers refuse to assign value to one interpretation of meaning without acknowledging the role they themselves play within this construction. This requires that researchers study the experiences, influences, and activities of research participants while explicitly and reflexively acknowledging their own personal biases. Yet the acceptance within qualitative research of the inherent bias of any researcher challenges the tradition of objectivity and threatens the potential for nonpartisan research. In addition, while privileging localized understanding through the inclusion of depth and detail, qualitative research sometimes proudly presents findings that would benefit from more rigorous analysis [390].

	Quantitative Approach	Qualitative Approach	Pragmatic Approach
Connection of Theory and Data	Deductive	Inductive	Abductive
Relationship to Research Process	Objectivity	Subjectivity	Intersubjectivity
Inference From Data	Generality	Context	Transferability

Source: Morgan (2007, p. 71).

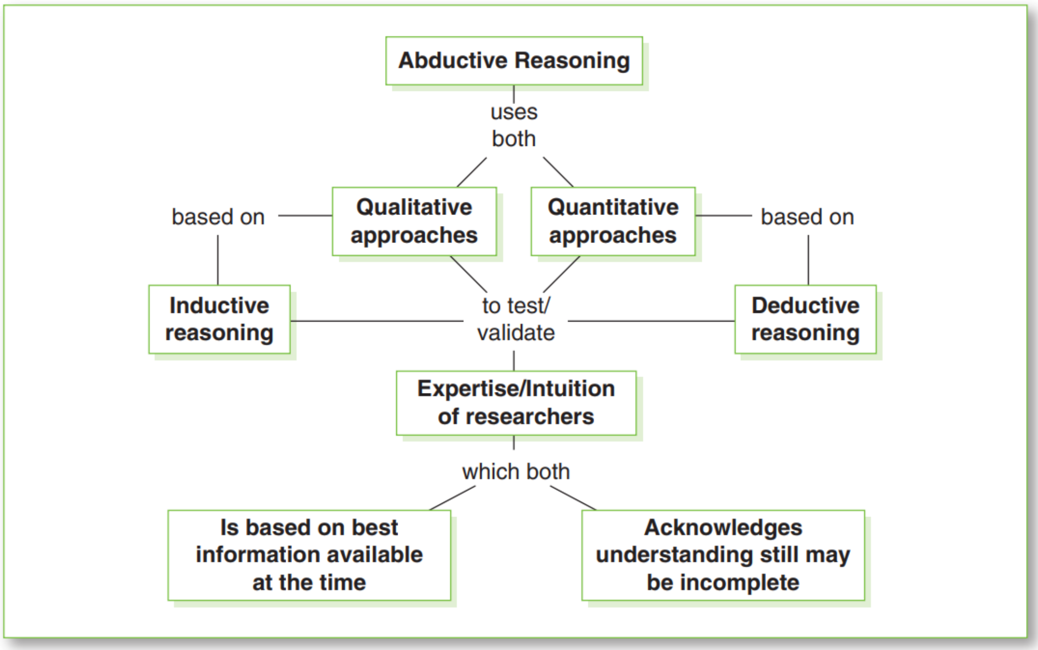

Figure 24: Above - Research approaches and methods explained **[390]**, Below- example of Decision tree in mixed methods research **[390]**.

Mixed-methods research is understood as an abductive process that values the expertise, experience, and intuition of researchers themselves; allowing multiple approaches, methods (and stages) of qualitative & quantitative data collection and analysis (see Figure 25). Mixed methods research is based on the premise of combining both the reliability of empirical counts and the validity of the lived experiences to get a better understanding of contemporary complex phenomena [390,412].

Mixed-methods research represents an important departure from the either/or assumptions of quantitative or qualitative approaches because it allows that both methods may be valuable depending on the type of research question under investigation [390]. Abductive reasoning can be understood as a process that values both deductive and inductive approaches but relies principally on the expertise, experience, and intuition of researchers (see Figure 21). Associated with mixed-methods research, through the intersubjectivity of researchers and their understanding based on shared meaning, this approach to reasoning encourages testing intuitions theoretically and empirically. Based on the best information at hand, tentative explanations and hypotheses emerge through the research process and can be developed and/or tested using methods that are either quantitative, qualitative, or a mix of both [390]. By relying on abductive reasoning, mixed-methods research offers an important new way to conceive of research and can produce more robust measures of association while allowing that multiple paths to meaning exist; escaping the trap of seeing research as an either/or choice between quantitative or qualitative designs [390].

Beyond benefits, there are a number of issues and considerations when following a mixed methods methodology. Three key considerations include timing, weighting, and mixing of the methods [390]. Timing refers to the timing of data collection (simultaneously & sequentially) and ordering of methods within a study. Sometimes these terms refer to when the data were collected and whether they were collected at the same time (simultaneously) or during different periods (sequentially).

Data collection and data analysis may not always be so closely intertwined. There may be times that data collected simultaneously are analyzed separately, in different ways, and at various times. Other studies might collect data through multiple data-collection phases over longer time periods. Weighing relates to how different methods are weighed in a study, or the relative importance of each approach. This is often indicated using capital letters for the dominant approach (quantitative or qualitative) and lowercase letters for the secondary, less dominant methodological approach (qualitative or quantitative). More often, one tradition is selected as dominant. Whether the approach is primarily quantitative or qualitative depends to a large degree on the type of research question the researcher is trying to address. Central to any research is how researchers justify their approach; relevant to the third consideration of (data) mixing. There are at least three options available when deciding how and why to mix qualitative and quantitative data. Data can be merged by transforming and/or integrating two data types together (qualitative & quantitative), one data type can be embedded within another, or they can be presented separately and then connected to answer different aspects of the same or a similar research question.

3.1.2. Design Research Methods

The next section discusses literature on design led/ Design Research methods relevant for many of the studies presented in this PhD Thesis, including design fiction, co-design (and co-creation) and prototyping and evaluating interventions. Design fiction is employed in Chapter 4, Co-design in Chapter 6, Co-creation in Chapter 8. Chapter 7 presents design research through the prototyping of an intervention and the documenting of the design process. Chapter 8 is closely related to Chapter 7, as it concerns prototype evaluation through the prototype's installation and deployment in-place.

3.1.2.1. Co-design and Design Fiction

Co-design (or participatory design) (see Chapter 6) in HCI can be described as a cooperative process that brings users and stakeholders together with designers to ideate technological solutions [182,235,334]. In co-design, users, experts or stakeholders are invited to participate in the design activities as designers; however, since they often lack the design training it is important to provide supportive materials – i.e. design tools such as templates and card kits -

to establish a common language between users and designers/researchers or experts from different disciplines, and help them with the design process [28,152,235].

Design projects can benefit from co-design sessions in various ways, e.g. it improves the creative process of ideation, and highlights perspectives & sensitivities of the users [28,235]; which is highly relevant when designing for Human-Centered Buildings and for the purpose of this project. Co-design workshops are often group activities involving storytelling, collages, cognitive maps, sketches or other indications of desired product features [28,235]. The co-design workshops are facilitated by design materials/ tools to provide entry points to the design problem and help the participants to envision and build their own design; engaging users and stakeholders not only to verbally describe ideas, but also make artifacts that illustrate the application of these ideas [235].

Ideation card kits are a common approach in co-design; used to engage non-experts with the design process. Cards are designed and provided to structure and guide ideation at the workshop sessions and to communicate framework categories to support ideation [130,320]. Relevant works illustrate the rationale behind designing card-decks as ideation toolkits [130,203] and results when used to facilitate workshops[200]. Card-kits have widespread design focus; including designing for wellbeing[96] [50,293]; evaluating workplace environments [202] and workplace wellbeing [95]; unpack broader relationships with the built environment in the context of IoT / smart buildings[28,88,190]- see Home Life Insight Cards for instance[97][233]; addressing issues including privacy [367] in such environments. Focusing on co-design & Ideation cards for IoT is of interest for this work [190]; past works include Cards'n'Dice, a playful method to explore basic IoT principles and create scenarios including sensors & actuators using a loaded dice and a set of cards; IoT Design Deck, designed to support during the whole design process of an IoT product or service from idea generation to creating the first prototype; IoT Design Kit, designed for companies that want to integrate IoT into their business utilizing strategy canvases and purpose made cards; KnowCards, which focus on making IoT functionality and interactivity accessible to non-technical minded users; Mapping the IoT, which focuses on the refinement of pre-existing ideas for problem-framing, concept development and evaluation; Tiles IoT Toolkit, which helps non-experts to generate ideas or invent IoT products in a short amount of time.

The above works were partly relevant with the framing of the workshop around data interactions in the workplace buildings, as they address in-place technology deployment, sensors and actuators; but they have less or no focus on architecture and built environment as a source of interactivity; or with the context of integrated wellbeing in the workplace. These gaps pointed towards the need to design a new card kit, to be able to contextualize the problem of human-data interactions and integrated wellbeing in the workplace. In terms of designing cards to prompt towards thinking the physical interactivity of building elements; a few works on affordances and shape changing interface design toolkits were considered; see broadly the

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[96] https://www.positivecomputing.org/blog/wellbeing-supportive-design-toolkit
[97] See Home Life Insight Cards at https://repository.lboro.ac.uk/articles/journal_contribution/Home_Life_Insight_Cards/4996541

work of Petersen on affordances [295] and shape changing interfaces design; Morphino [303], bioinspired card-based toolkit for designing shape changing interfaces; and Design-Heuristics[98], a card kit mostly targeted on industrial design / product design, also addressing affordances and physical manipulation of the lived-in environment as a source of design inspiration. Similarly, these works did not address the workplace or wellbeing and were partly served as a source of inspiration.

Recently, co-design is methodologically explored together with Design fiction [73,248,270] in very limited works. Design Fiction [175,201,366] (see Chapter 4) is the deliberate use of diegetic prototypes to suspend disbelief about change. In Ubicomp research, Dourish and Bell [201] have pointed out the particular relevance of science fiction to design research and - potentially co-design - because of its "explicit focus not only on the extrapolation of current technological opportunities, but the imaginative and speculative figuring of a world in which new technologies can be applied"[175,366]. Design Fiction has never been strictly defined as a design methodology and process; Johnson provides "Five Steps" to develop a Science Fiction Prototype[99] [175]- which have been used to structure storytelling activities. In this work, and in order to investigate feedback strategies within the context of integrated health and wellbeing in the buildings; the building elements, spaces and objects obtain the ability to be highly interactive – which gives this co-design study a highly speculative, design fiction approach. This was supported by the design of specific 'inspiration cards' which served as diegetic prototypes; as described in Chapter 6, section 6.3.3.

3.1.2.2. Prototypes and Prototype Evaluation in HCI research

The justification behind the making (see Chapter 7) and the deployment of a prototype in-place (see Chapter 8) as response to a set of problems or research questions, is framed within Pragmatism and Design Research [129]. Pragmatism as a methodological approach is heavily concerned with knowledge of the world "to-be" [129]. Design research also fits within this lens, as it can described as the process of knowing of the world-to-be through the making and deployment of prototypes [129]. The making and deployment of prototypes embodies the designers/researchers attempt to intervene into the world/present, and install a possible world/future [129].

Prototypes illustrate examples of technology in-progress [388], illustrating ideas and concepts of technology to-be [265,297]. No matter their fidelity or presentation [297], prototypes serve as manifestations of theoretical concepts and instantiations of a future outcome. Acting as references for future worlds and theoretical concepts, prototypes in HCI research are not evaluated for what they are, but rather their potential to become [265]. Through their evaluation, knowledge about the prototype itself and the potential of the theoretical/technological concepts that it embodies to change the future is generated [388].

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[98] https://www.designheuristics.com/the-cards

[99] The five steps include: (1) Pick your science and build your world (2) The scientific inflection point (place your technology into your world) (3) Ramifications of the science on people (4) The human inflection point (characters at their wits' end) (5) What did we learn?

The introduction of prototypes in design research as actionable responses to real problems is a generative process of creating knowledge about the world-to-be [324,388]. Through their making and their evaluation knowledge about the possible future is generated, as well as knowledge about the prototype itself and the potentials of the theoretical/technological concepts that this prototype embodies. In other words, the construction of a prototype contributes knowledge about the design problem; while empirical evaluation of the prototype contributes knowledge about its capacity to change the world in the future. Goldkuhl et al. [129] refers to this aspect of design research, establishing three kinds of pragmatism[100] (functional, referential and methodological) that follow three types of relations between knowledge and action - i.e. prototype making & deployment, and knowledge around it [129].

What constitutes a prototype and how it is deployed into the real world varies in a great extend in design research; with many different degrees of implementation, use and evaluation [129]. Unpacking what a prototype is and how it is presented, Pierce [297] distinguishes the prototypes into operational prototypes/products, material and conceptual design experiments & studies, and design proposals. The first category has end-users as an audience, implying that the prototype has a high degree of technical and practical autonomy [297], ready to be used in the real world. The second category refers to artifacts that are need a great level of scaffolding to make sense of; having a lesser degree of autonomy to operate outside a community of interest – i.e. the designers /researchers themselves, who are framed as the end-users. The third category speaks about design concepts as prototypes, primarily used for communicating research. He further discusses how these different prototype categories are linked to knowledge – constituting, containing and constructing knowledge [297].

Odom et al. [268] further addresses the long-term deployment of highly operational prototypes and their potentials to shape human relations with technology (evolving with their users) [265,370] introducing the term 'research product' [268]. Distinguishing from prototypes (technology to-be), they define research products as technology 'as is' [268]. According to Odom et al. [268], a research product has four core characteristics: drives a research inquiry through its making and experience (as a prototype), has a high level of finish and clarity in terms of how it is perceived and used, it is fit to be lived-with and in everyday conditions over time – therefore it is neither too familiar nor too strange, and is independent, meaning that it can be freely deployable in the field for the long term with no intervention [268].

A gray area in HCI research is the evaluation of the prototypes [136,324] (see Chapter 8). Design research embraces the installation of the design output into the world in order to evaluate it, aiming to produce knowledge in a two-fold way: on one hand, HCI research strives to increase knowledge of the design of interactive computing systems; on the other, it studies 'phenomena surrounding them'[324]. Therefore, it is important to clarify that evaluation is a much more generative process than merely a useability evaluation [136]. Following Greenberg

[100] Functional pragmatism means knowledge for (improved) action; referential pragmatism means knowledge about actions; that knowledge is formulated in terms of actions. Methodological pragmatism means knowledge through action; that knowledge is created through action.

& Buxton [136], useability evaluation can be ineffective and even harmful if naively done ‘by rule’ rather than ‘by thought’. If framed around validating an academic prototype, it should not exclude a broader meaningful critique of how it would be adopted and used in everyday life; and with a view for long-term technology adoption. In their own words, the choice of evaluation methodology must arise from and be appropriate for the actual problem or research question under consideration [136]. For instance, they suggest that design crits are relevant for early-stage evaluations opposed to more controlled experiments as the design progresses.

Another methodological problem around the evaluation of the prototypes in HCI research is what Salovaara et al. address as the present-future gap. Given that a prototype is considered as a placeholder for the future, an evaluation of a prototype is a study of ‘what might be’. As a result, any evaluation needs to consider the uncertainty of the future (either near or distant), *‘facing the problem that the future must be somehow enacted in the present if one is to draw conclusions about it* [324]*’.* This is a potentially significant problem in terms of generalizing observations; creating issues of scientific validity. Salovaara et al.[324] propose the following principles as a pathway to addressing it; a) change of mindset: understanding the prototype in plausible futures; b) reflection: considering evaluation methods that allow staging and customizable control (inhibiting features that conflict with the future); c) emphasizing in replicability in the future (as a way to validate results); d) associated transparency of any assumptions about the future; e) post-launch monitoring of a given prototype in context over time.

In Design research in Human-Building-Interaction and Adaptive Architecture, prototypes are often deployed to conduct lab experiments [330], case studies and long-term deployments in the wild [57,370], aiming to generate knowledge about the prototype/intervention and human behavior around it. As an example, ExoBuilding [330] illustrates the deployment of a prototype (an interactive tent-like structure) and a series of controlled experiments to observe aspects of human behavior based on biometrics. Many of these works face limitations with regards the generalizability of the results [324] outside a controlled context, failing to address the long-term implications of lived-in technology in place [370,421] – i.e. the lived-in technology in context over time and its potential future implications.

Summarizing, the evaluation through deploying a physical prototype is a more generative process than merely a usability evaluation [136]. Human-technology relationships in the lived-in built environment develop over time; as a result, evaluations that present controlled studies within limited timeframe have profound limitations.

3.2 Methods and Activities overview

Below is a short overview of the methods, the studies and activities that took place in each chapter. The two sections , Section B: Understanding People in Place; and Section C: Understanding Materiality: Design & Material Explorations both provide Empirical findings and Design contributions. The findings from Section B inform and drive design research in Section C. Section C responds to key findings from Section B through Design Research. This is not done on a "one to one" basis; it is a generative response on the key findings through Design Research as discussed in section 6.4.5.

Section B "Understanding People in Place" has 3 chapters, each of which addresses human experiences in a different spatial context: in office buildings (Chapter 4), in the domestic office (Chapter 5), and in both – in hybrid (Chapter 6). In that way, Chapter 6 serves also as data-triangulation chapter; meaning that it repeats and validates findings and observations from the previous two Chapters (4 & 5) while also preparing the ground for Chapter 7 "Design Research"; through co-design activities to better frame design-related contributions from Chapters 4 & 5. The order of the chapters matches the chronological order of all studies and activities that took place throughout the PhD.

Section C "Understanding Materiality: Design and Material Explorations" comprises of Chapter 7 – the material exploration which resulted in prototyping ActuAir – and Chapter 8 – three studies to evaluate ActuAir in-place.

Section 1.4.1 provides a more detailed overview of each Chapter and the studies and activities that take place. The next sections discuss the complementarity of studies and the rationale behind the choice of methods to accomplish those studies through the use of diagrams. Moreover, recruitment and participation trends are discussed, together with the relevant limitations with regards to scalability of findings.

3.2.1.Methods and Studies: Rationale, Complementarity, Relatedness.

Following a pragmatic lens, this PhD has engaged with mixed methods and ways of collecting and analyzing data; which varied depending on the research question and research context of each set of studies as presented in each Chapter (as presented in Section 3.2.). The choice of the methods and data collection processes was not planned a-priori; it organically evolved around my attempts to respond to the research questions through following a high-level design iteration frame (Understand-Define-Ideate-Prototype-Evaluate design phases), while adapting to the context and what was available in each case.

Overall, in Section B, Chapters 4-6, I introduce the framing of each of the studies from scratch to participants; without relying on their previous knowledge. Similarly, the studies in these Chapters do not seek to inform or build upon each other's findings, instead, they seek to address the research questions through exploring different aspects of quantification and wellbeing in a changing workplace which will then later be synthesized in design implications to guide prototyping. On the other hand, Chapter 7 and Chapter 8 are related in a more systematic manner. Chapter 7 responds to empirical findings through prototyping. Chapter 8 evaluates the prototype, through a series of interconnected studies that inform each other as described in section 8.2. The high-level rationale and the methods used in each chapter and studies are described below (showcasing studies' relatedness/complementarity) illustrated in Figure 26, for clarity and replicability purposes.

In Chapter 4: Understanding occupants' experiences in quantified buildings, qualitative data were obtained through focus groups and design-led methods (Design Fiction); to map the (subjective) sensitivities of the building occupants of a smart office building and draft the landscape of potential design interventions in the building, generalized to similar smart office buildings. The choice of methods was justified given the broadness of the research question and to form a basis for understanding human experiences in context and guide future design work in this space. The studies were introduced as independent entities to participants; and although participation in more than one study was encouraged, it was not a prerequisite. Data was collected sequentially (a series of studies which explored related subjects framed under the quantified buildings theme as described in section 4.2.3, with more material found in the appendices) and was qualitatively analyzed together. Findings from all studies are presented and discussed together (as one analysis) in sections 4.3, 4.4, while signposting to which study each of the findings relate to. The findings of this chapter do not directly influence the framing of the study of Chapter 5; but frame themes and design patterns to further explore in Chapter 6.

In Chapter 5: Mapping the experiences of building occupants in the remote workplace; the research aim (i.e. mapping experiences over time) and context (domestic, non-shared workplace) justified the employment of data collection tools such as web diaries (self-reporting qualitative and quantitative measures) and wearables (quantitative data). Both types of data were collected simultaneously over a longer period of time (4 weeks). Quantitative and qualitative data were analyzed independently but simultaneously; and are presented in equal terms. The discussion has a stronger quantitative focus – i.e. using the quantitative data to inform qualitative observations. The findings inform the theme of the co-design study in Chapter 6, in the sense that some design considerations are translated into potential design patterns through the card-kit, to further explore with participants.

Chapter 6: Co-designing for wellbeing in the hybrid workplace presents two studies: a focus group activity using sticky notes and a co-design workshop using a custom card-deck. The theme of the studies has been informed by the previous chapters - i.e. bringing some of the design directions through the card kit aiming both to validate past findings and solidify design directions with participants. However, as with previous chapters, this chapter also introduces the subject independently. Data was sequentially collected through the two studies exploring the same high-level theme. Sticky notes and card-decks inherently provide opportunities for both qualitative and quantitative data analysis – i.e. the repetition of the use of specific cards brings quantitative insights, while the scenario or context in which these cards are used and discussed by participants provides with qualitative insights. Data was qualitatively analyzed – first, each study independently and then together. At a first stage, data collected in focus group study and co-design were subject to a Content Analysis [224] (each study's data set separately); while co-design data were also subject to a visual thematic analysis – as per [46]. After unpacking main patterns in the data; the two data-sets were merged and thematically analyzed together; resulting in the themes discussed in the Chapter. The Chapter provides a summary overview of all key findings of previous studies, to guide the next design research phase.

Chapter 7 is primarily design research led, responding to key findings from all empirical chapters (as showcased in section 6.4.4) through design research. The design process is extensively documented in this chapter, following a portfolio approach.

Chapter 8: Design Evaluation is tightly linked with Chapter 7. In this Chapter, three successive studies to evaluate the design intervention developed in Chapter 7 are presented. These studies consist of design criteria focus groups, a co-creation workshop, and a case study of a deployment; all facilitated by the prototype's installation in-place. Qualitative data was collected sequentially and was thematically analyzed following a similar model as presented in Chapter 6. At the first stage, data of each study was subject to a Content Analysis [224] (see supplementing material) to map general trends and broader insights. Qualitative data were then combined to one data set, and were subject to a Thematic analysis [33,216] (which is the analysis presented in the Chapter) to provide a more interpretational in-depth understanding of the data. As the research question that this Chapter addresses is design-oriented (RQ3), design-led data collection methods were preferred. Thematic analysis was preferred as the final data presentation method, as it was more interpretational and allowed space for generating design considerations for future research. Similarly to Chapter 4, all results are signposted to show which of the studies do they relate to.

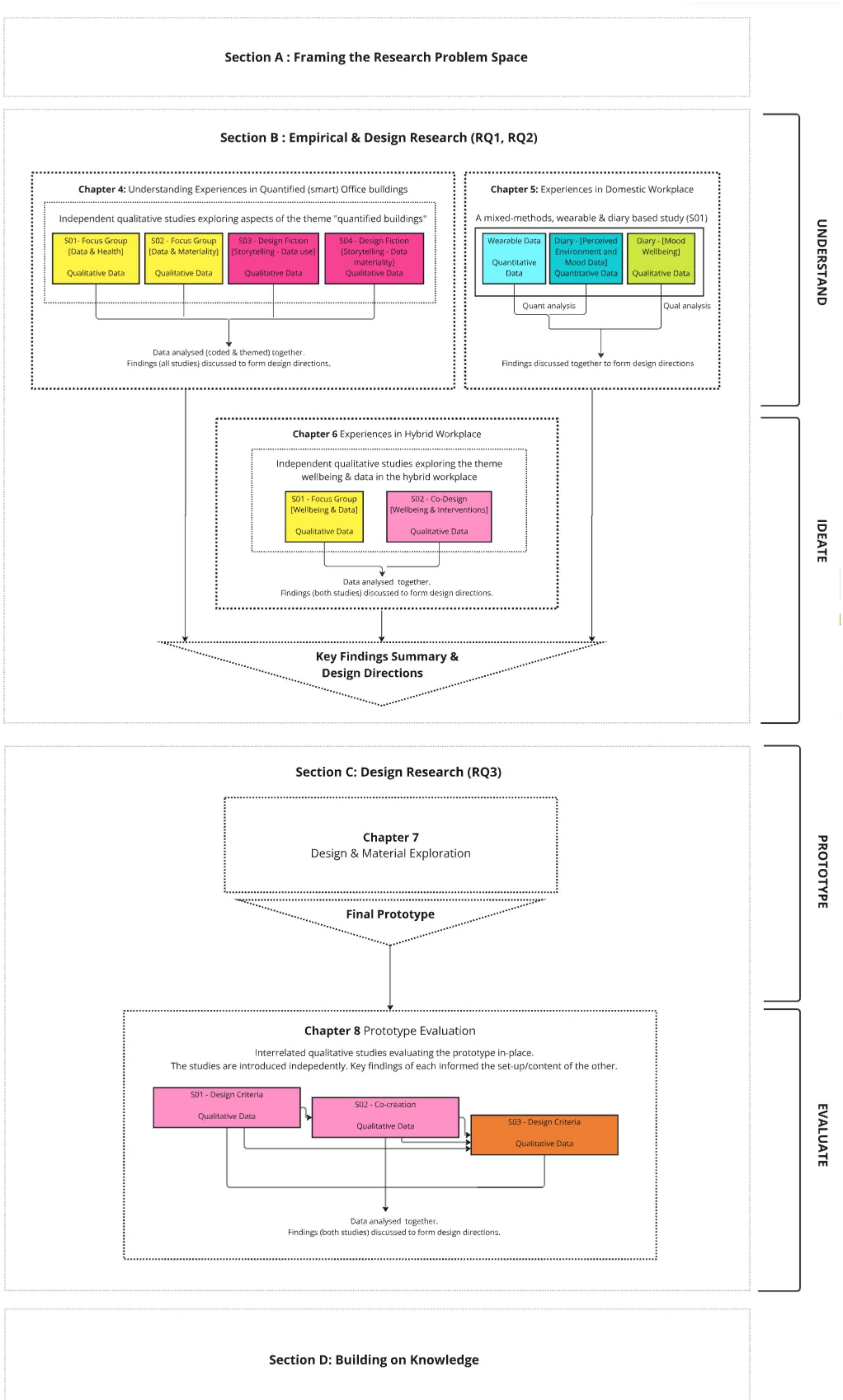

Figure 25: Empirical and Design Research Chapters -Studies and methods. As shown, most of the studies are exploring different aspects or dimensions of a central theme, but are introduced independently (see Chapter 4, 6). In Chapter 8, the studies inform each other (set up and content

informed by key findings of the previous). A mix of focus groups and design research methods are employed in Chapter 4,6. In Chapter 5, a mixed-methods approach is employed.

3.2.2. Recruitment, Participation and Relevant Limitations

For all studies, recruitment was done through email or social media, or by word of mouth followed by snowball effect. Most of the participants were employees, contractors or frequent visitors to the same workplace building, which made recruitment easier. Given that the building is predominately a research facility/teaching space; there was a frequent change in the staff with many students/researchers and research visitors being employed on short-term contracts and only a few being permanent academics. This fact mitigated systematically recruiting the same participants for all studies. Figure 27 below shows the participation trends throughout the duration of this PhD work; recruiting 57 participants in total. As the figure shows, only 2 participants have been recruited in studies across all 4 empirical Chapters; another 3 participants have participated in studies spanning across 3 empirical chapters, and 5 more have participated in studies in 2 empirical chapters.

Due to COVID and as this took place over a 4-year timeframe, different participants participated in this work's studies. I consciously and actively made decisions to recruit participants that have not been previously exposed to my work to eliminate biases – unless the studies were presented as a series of related workshops. For instance, in Chapter 4, studies were introduced as independent from each other but were related in terms of the overall theme they were exploring - which was the different dimensions of the quantification of the buildings, as presented in section 4.2. Each of my studies introduced the subject from scratch to establish a common basis for all; but previous participation was not seen as problematic, rather than the opposite. The same strategy was followed in Chapter 6, but not in Chapter 8. As the studies in Chapter 8 were around ActuAir prototype's evaluation - not around a speculative subject such as in Chapter 4, or an ideation/design study such as in Chapter 6- participants were chosen more carefully. As I describe in section 8.2, participants with no previous exposure to any of my design fiction or co-design studies were selected for the prototype's evaluation studies (Chapter 8, studies 01 and 02). Moreover, I made sure that participants were different in each of these studies as shown in Figure 27.

One of the key factors influencing my findings (and could be framed as a limitation of this work) relates to the profession/expertise of my participants, which was often relevant to the content of the studies. As the Figure 27 shows, many of the participants had expertise in HCI/interaction design, which influence their knowledge (and views) around data use in the buildings. I used my participants' expertise to my advantage where appropriate – see expert design criteria Study 01 in Chapter 8.2 for instance, or for design-fiction (Chapter 4) and co-design (Chapter 6) studies. Given the scope and exploratory nature of this work, the participant's expertise is not treated as a limitation but is acknowledged as a factor that influences my findings.

	Participant Number (per Chapter)				Study Numbers that participant took part				Attendance Mode	Gender	Age Range	Profession / Expertise
	C4	C5	C6	C8	Chapter number -Study number							
1	P01				C4 -S01				physical	m	20-30	social science / HCI
2	P02				C4- S01				physical	m	20-30	social science / HCI
3	P03				C4- S01, C4-S02, C4-S03, C4-S04				physical, online	m	30-40	social science / HCI
4	P04	P13	P08		C4- S01, C4-S02, C4-S03, C4-S04	C5 - S01	C6-S02		physical, online	m	30-40	data science / behavioural science
5	P05				C4- S01, C4-S02, C4-S03				physical, online	m	30-40	architecture, planning / HCI
6	P06				C4- S01				physical	m	40-50	Academic / Interaction Design
7	P07	P01	P01	P18	C4- S01	C5 - S01	C6-S01	C8-S03	physical	m	40-50	social science / HCI
8	P08				C4- S01				physical	m	20-30	VR/AR / HCI
9	P09	P04	P02	P19	C4- S01, C4-S02, C4-S03	C5 - S01	C6-S01	C8-S03	physical, online	f	30-40	project manager
10	P10				C4- S01				physical	m	30-40	education /entrepreneur
11	P11				C4- S01				physical	m	20-30	social science / HCI
12	P12				C4- S01				physical	m	30-40	software/ hardware enginner
13	P13				C4-S02, C4-S03				online	f	20-30	bioinformatics
14	P14				C4-S02, C4-S03				online	m	30-40	digital health
15	P15			P17	C4-S02, C4-S03, C4-S04			C8-S03	online	m	40-50	social science / HCI
16	P16				C4- S02				online	f	30-40	education / HCI
17	P17		P09		C4- S02		C6-S02		online	m	20-30	social science / HCI
18	P18				C4- S02, C4-S03				online	m	30-40	digital health
19	P19				C4- S02				online	f	20-30	social science / HCI
20	P20				C4- S02				online	m	20-30	social science / HCI
21	P21	P07	P10		C4- S02, C4-S03	C5 - S01	C6-S02		online	f	40-50	education, IT management
22	P22				C4- S02				online	m	30-40	Academic / Interaction Design
23	P23		P05		C4- S02		C6-S01		online	f	30-40	digital health
24	P24				C4- S02, C4-S03				online	f	20-30	data analysis, digital health
25	P25				C4-S04				online	f	30-40	IoT expert
26	P26		P04	P16	C4-S04		C6-S01	C8-S03	online	f	20-30	social science / HCI
27	P27				C4-S04				online	m	20-30	social science / HCI
28	P28				C4-S04				online	f	30-40	architecture, social science
29		P02		P04		C5 - S01		C8-S01	online	f	30-40	Interaction Design
30		P03				C5 - S01			online	f	20-30	Interaction design
31		P05				C5 - S01			online	f	30-40	IT manager / software engineer
32		P06				C5 - S01			online	f	20-30	psychology
33		P08				C5 - S01			online	f	30-40	architeture
34		P09				C5 - S01			online	f	30-40	research
35		P10				C5 - S01			online	m	30-40	medical economist
36		P11		P15		C5 - S01		C8-S03	online	m	30-40	machine learning
37		P12				C5 - S01			online	m	40-50	behavioural science
38			P03				C6-S01, C6-S02		online	m	20-30	software enginner
39			P06				C6-S01		online	they	30-40	social science / HCI
40			P07				C6-S01		online	they	20-30	User experience designer
41			P11				C6-S02		online	f	20-30	Interaction Design student
42			P12				C6-S02		online	f	20-30	Interaction Design student
43				P01				C8-S01	physical	m	30-40	software engineer
44				P03				C8-S01	online	m	30-40	hardware / interaction design
45				P03				C8-S01	physical	m	40-50	Academic / HCI
46				P05				C8-S01	online	f	40-50	Academic / Interaction Design
47				P06				C8-S01	physical	m	40-50	Academic / Design
48				P07				C8-S01	physical	m	30-40	hardware / interaction design
49				P08				C8-S01	physical	m	40-50	software / hardware egineer
50				P09				C8-S01	physical	m	30-40	Academic / HCI
51				P10				C8-S02	physical	m	20-30	HCI student
52				P11				C8-S02	physical	m	20-30	HCI student
53				P12				C8-S02	physical	m	20-30	HCI student
54				P13				C8-S02	physical	f	20-30	HCI student
55				P14				C8-S02	physical	m	20-30	HCI student
56				P20				C8-S03	physical, online	f	20-30	HCI
57				P21				C8-S03	physical, online	they	20-30	Interaction Design

Figure 26: Participation trends throughout the studies conducted.

SECTION B. UNDERSTANDING PEOPLE IN PLACE

EMPIRICAL RESEARCH FINDINGS

Chapter 4. Understanding occupants' experiences in quantified office buildings.

4.1. Introduction

In this chapter, I provide the starting point for research on the timely issue of the quantification of and in the workplace; contributing to the limited works in HCI and HBI research on the building occupants' experiences of lived-in smart office buildings. My research aim in this chapter is to map aspects of the experiences of the building occupants of one quantified "smart" lived-in office building, and develop an understanding of their perspectives, concerns, and values on data collection and its use within the building. Responding to RQ1 and RQ2, in this chapter I present and discuss findings from a series of four (4) exploratory studies with 27 occupants of a shared workplace based at a smart office building.

4.1.1. Research Context

The term 'quantified building' describes the infusion of digital technology in the lived-in built environment and the phenomenon of increasingly inhabiting 'smart' buildings [215]. The term "quantified" [63,97,222,247,316] highlights the intensification of data collection on building performance and human activity in these buildings; facilitated by recent technological developments in the Internet of-Things and Building Management Systems such as BIM (Building Information Modelling) [171,310,312] supporting the so-called 'smart buildings' agenda [44,124,126,231]. Smart buildings support data collection, processing and use as a means of quantifying and optimizing building microclimate, energy consumption, maintenance and use [15,310,312,332] and more recently, building occupants' health and wellbeing [10,315,332,353].

The quantification of the built environment occasions possibilities for research in the field of Human-Building Interaction (HBI) research [142,143,313,337]. The implications of the quantification of the built environment for the building occupants is of significant interest and relevance for HBI research. Using sensing technologies, researchers can generate, access and utilize data footprints around buildings and building occupants [310,331,332] e.g. combining environmental data from embedded building sensors and activity data from fitness monitors and smart phones [145,210,356]. Such data footprints, suitably mined and modelled, have the capacity to provide important information about the dynamic and time-bound nature of individual and collective behaviors of individuals currently and (perhaps importantly) previously, within the buildings [32,61,265,266,421], with attendant ethical and human concerns for how this data should be handled and (re)used [67,99]. Lived-in smart office buildings in particular [8,185,257] present new sites of digital interaction through accumulating and using data in the workplace; with particular opportunities for wellbeing and social interactions [9,42,74,422], and concerns and challenges for employee privacy [5,26,99,133].

The smart office building that is the center of this research can be described as a quantified 'living lab'[8,185]. It is a lived-in office, study and research building part of university, developed with the potential of being a research facility – albeit not explicitly stating so. Being highly monitored, the building provides the ground data infrastructure for HBI research and diverse data use applications to take place; while operating as an office/university building. The sensory infrastructure has been developed with regards to building owners' and building manager's needs for building operation management, and with a view to be shared for research projects. The data is accessible through a public API[107] to researchers and building users. Due to the data formatting which requires a level of technical knowledge, the lack of information around data collection and use and the limited involvement in decision making regarding the above; the frequent users of the building have little awareness and understanding on what data is collected and how it is used in the building. This is often the case in many smart offices; with the employees feeling 'monitored' [26,99] and that their privacy is threatened by the excessive data collection taking place- even if this data is not linked to their activities.

Beyond this specific building case, there are plenty examples where the line between research infrastructure and lived in smart building is hard to be drawn [8]. In some cases, what differentiates a living lab from a lived-in smart building is the data access and ownership, the access to the space and infrastructure, and the focus and scope of a potential research agenda for the place [8,75]. The Edge [171] could be seen as such an example, similar to the office building used in this work. The availability of the open datasets and access to lived-in quantified workplaces creates great opportunities for HBI research [9,143,222]. But the reality of lived-in smart office buildings has unresolved complexities with regards to their users' experiences, such as the feeling of control on their environments [231,251], and perceived and actual privacy [26,99,133,193,251,261]; where is one of this work's contributions.

4.1.2. Research Questions

Within extant research, the quantification of the built environment and in the built environment; and its impact on the daily experiences of the building occupants within smart workplaces remains, to date, widely unaddressed by HCI and HBI research [216]. To support the design and development of future human-centered quantified workplaces, it is vital to understand what constitutes current and emerging occupant experiences of such lived-in smart buildings, and what occupants expect or value from a quantified building. To address this research aim, this chapter responds to the following research questions:

- RQ1: What are the experiences of the building occupants in the quantified workplace? (RQ1a: What are the experiences of the building occupants of a quantified (smart) office building?) and

[107] See https://3d.usb.urbanobservatory.ac.uk/

- RQ2: How do their experiences inform data use for wellbeing in the buildings for work (RQ2a: How do they view data collection and use for health & wellbeing in the building?)

Responding to RQ1(RQ1a) and RQ2(RQ2a), I provide and discuss results from a series of four (4) exploratory studies that happened during January and April 2020, with twenty-seven (27) occupants of one "smart" quantified office. Workshops used qualitative techniques to explore occupants' conceptions of, and concerns around, the collection, processing and use of data – e.g. environmental or health data - in a shared workplace; and projective (including design fiction) techniques, to help understand attitudes towards spatiotemporal contingencies of collecting, archiving, and interacting with data in the buildings.
COVID-19 had an attendant impact conducting this research. Under a pragmatic methodological lens, I treated COVID-19 as a variable to be addressed through the appropriation of my research methods. Many of the workshops were therefore conducted online; meaning that virtual tools had to be employed to address the subject and engage the participants effectively – i.e. providing them with the experience of a shared spatial context.

4.1.3. Research Contributions

This chapter unpacks the occupants' experiences of a smart office building around data collection and use in the building; broadly, and with a focus on health and wellbeing. Doing so, it provides with empirical and design-oriented research contributions to the field of HBI research [143]. In terms of the empirical contributions, it provides insights from the occupants' experiences of a lived-in smart (quantified) office building; highlighting pressing research challenges for the human-centered development of smart buildings. These primarily relate with the complexities of perceived privacy, and data awareness, accessibility, and use for health and wellbeing. Key findings include observations on how physical scale and scale of data inform perceptions of privacy; the confusions with regards to what data is personal; the perceived underutilization of data for the occupants' benefit and use which emphasizes on making data visible and tangibles in the buildings; and the conflicting views over AI-driven and user-driven control of data use for health and wellbeing in the buildings. Finally, based on these findings, I provide considerations for developing a design and intervention-oriented agenda for human-centered smart office buildings; focusing on design recommendations for improving perceived privacy and data awareness that address the physical and material dimensions of the built environment.

Summarizing the key design & empirical contributions to HBI research field:

- Responding to RQ1, I provide empirical contributions to the limited number of studies in lived-in smart (quantified) office buildings by unpacking the experiences and perceptions of the occupants on data collection and use.
- Responding to RQ2, I provide empirical contributions regarding the collection and use of data for health and wellbeing in workplace buildings from the perspective of their users.

- Responding to RQ1&RQ2, I propose directions for a design research agenda for the human-centered development of similar smart buildings.

While acknowledging the work's limitations in terms of scalability of the findings to all smart buildings, its novelty lies in exploring the complexities of a lived-in smart building - as opposed to a lab set up – from the perspectives of its occupants; and attempting to address these through a design-oriented research approach. Given that there are very few studies in real smart offices [8] due to either the restrictions in physically accessing these buildings, or due to limited or restricted access to data generated by and in these buildings; this work offers a unique contribution to the field of HBI research.

4.2. Methods

To address the above research questions, I developed a series of four workshops. The aim of the workshops was to formulate a 'set of user sensitivities' to guide the design of future interventions and design research on smart office buildings. To facilitate the workshops, I employed a range of qualitative research methods such as Focus group discussions, Design Fiction and Story Telling activities [366]. I chose to engage with these methods as a means of expanding the design space of quantified environments; facilitating the building occupants' narratives of their experiences in the building. During the workshops, participants protectively explored perspectives of data collection and use in the built environment, highlighting underlying concerns, ethical considerations, values, and attitudes towards quantified buildings. The outcome of the workshops was a series of narratives of both present as well as fictional experiences in quantified buildings - utopian and dystopian scenarios, projecting underlying concerns through an exaggerated and polarized manner [366]. These narratives highlight current problems and opportunities of human-data interactions in the quantified built environment from the perspective of the users.

The workshops were designed as an evolving program of work, aligning with a pragmatist orientation to research [129]. The design of the workshops also purposely framed aspects of the experiences of and around data collection and use in the buildings under distinct themes: the experience of the temporal dimension of data, the experience of the materialization (or materiality) of data, the experience of the physical dimension of data, the experience of the scale of data (either physical or digital), the quantification of health and wellbeing, and data-driven reactivity or interactivity in the buildings. One or more themes were explored in each of the four workshops, employing relevant research methods and tools.

Each of the workshops contributes towards a design research agenda for human-centered quantified workplaces through employing a different angle and methods. The first workshop (focus group) focuses on the current data collection and use practices in a smart office building; focusing on the data experiences at present. It highlights aspects of scale of data collection (i.e. physical scale and mass of data), and addresses perceptions around the quantification of health and wellbeing in the workplace. The second (focus group) explores the temporal scale of data and the materialization of data over time in the build environment. Scale and value of data is discussed through an emphasis on the temporal dimension of data collection and use in the buildings. The third workshop (design fiction) further explored scale of data and quantification of health and wellbeing; allowing participants to envision their own utopian & dystopian scenarios of smart buildings though story telling. The fourth workshop (story telling) explored data interactivity, reactivity and data physicalization provided participants with images of interactive architectures, engaging them in then writing stories on how the environment can adapt / interact with the users based on data. The exploratory nature of this work justifies the selection of such broad methods and themes, aiming to understand and widen the design space of quantified environments.

4.2.1.Study context

The building[109] where the studies took place is a five-floor modern office building in a city in the UK, which has been advertised and is widely known as a smart building. It is a highly sensing and monitoring environment with an extensive array of embedded environmental and occupancy sensors. The building is part of Newcastle University, hosting office, teaching, event-space, and research facilities; while the ground floor is an atrium open to public and often serves as event space. Although not explicitly built as a research facility/living lab, the building works as such: it is built to both serve as a real workplace while providing opportunities to conduct research with the data. Data is logged publicly via an API[110], allowing open access to real-time and historical (timeseries) data of different spaces in the building.

4.2.2. Participants

Participants (Tables 1 and 2) were recruited from occupants of a shared workspace based at the office building above. Participants were employees, researchers and students working in the same space. Their familiarity with regards to data and software/hardware varied; none of them could be characterized as an expert, but many of them had relevant knowledge on broader technology and data disciplines – e.g. HCI research. Participants were all aware of what the building monitors, but had very limited previous exposure to, or interaction with, the data produced. Participants were not recruited based on their technical knowledge and data familiarity but based on them being full time workers at the same open plan office space hosted in this building for a period greater than 6 months (minimum was 6 months, greatest was 3 years). In that sense, participants were treated as a community of interest because of their lived-in experience of a smart building. Finally, participants were not incentivized to take part in the workshops.

4.2.3. Studies

The four (4) workshop studies were conducted during January, February, and April 2020 (Table 1). Workshops lasted between 30 and 60 mins. The first workshop took place physically,

[109] https://www.ncl.ac.uk/cesi/research/demo/usb/
[110] https://api.usb.urbanobservatory.ac.uk/ and https://3d.usb.urbanobservatory.ac.uk/

while the rest were conducted online using Zoom Software due to COVID-19 lockdown. Each workshop was treated as a separate entity, starting with a presentation framing the 'smart buildings' agenda and problem space, and then continuing with a specific angle and method as described in the above section. Participants were introduced to the building's API[111] at Workshop 1 and were encouraged to interact with the data. Participants were also encouraged to take part in most of the workshops – e.g. many participants in Workshop 2 also participated in Workshop 3.

The workshops were designed as a program of work that would organically evolve over time, responding inductively to participants' output and expressed concerns and interests. Methodologically, this aligns with a pragmatist orientation to research, eschewing an a-priori determination of experimental variables to be tested. I deliberately chose to have a level of freedom to adapt to changing circumstances - such as the move to remote data collection during COVID-19 lockdowns and the varying interests and engagement levels of the participant pool. Accordingly, participants' recruitment also evolved as I progressed with the studies. For instance, focus groups had the form of an open discussion driven via a presentation for anyone wishing to attend, without a strict requirement on the number of attendants. Other activities such as the design fiction in Workshops 3,4 had different requirements as the format is easier to manage with a small number of participants; therefore, I kept the overall participant number open but divided them in subgroups of 2-3 participants per group.

Instead of narrowing the participants to specific data outputs/streams or specific data-uses cases/applications, I purposefully used abstraction as a technique to unpack participants' broader values and concerns; e.g. using fictional characters to enable story-telling, similarly the use of the visual representation of sensory devices instead of the actual data streams to avoid anchoring in specific technical aspects.

Using Zoom as the main communication channel had pros and cons: remote engagement enabled wider participation but limited in the ways people collaborated and interacted with each other. Tools had to be invented to provide the participants with a common spatial context (office) during story-telling activities – such as the development of the 360 toolkit (see Workshops 3, 4). Overall, participants seemed to perform well when working in smaller groups via zoom rooms. Participants also reported that being able to develop their stories at their own time using online material allowed space for in-depth thinking and self-reflection.

[111] https://api.usb.urbanobservatory.ac.uk/ and https://3d.usb.urbanobservatory.ac.uk/

Table 1: Studies Set up

Workshop	Format	Description	Participants	Duration
Study 01 (S01)	Office space	Focus Group discussion	12	40’
Study 02 (S02)	Zoom Software	Focus Group discussion	15	35’
Study 03 (S03)	Zoom Software	Design Fiction and Story-telling activity	10 (4 groups)	60’
Study 04 (S04)	Online (webpage)	Design Fiction and Story-telling activity	7	30’

Table 2: Participants (gender and occupation shown in brackets)

Study 01(S01)	Study 02 (S02)	Study 03 (S03)	Study 04(S04)
P01 (m)	P13 (f)	P13 (f)	P24 (f)
P02 (m)	P14 (m)	P14 (m)	P25 (f)
P03 (m)	P03 (m)	P03 (m)	P03 (m)
P04 (m)	P04 (m)	P04 (m)	P04 (m)
P05 (m)	P05 (m)	P05 (m)	P26 (m)
P06 (m)	P15 (m)	P15 (m)	P15 (m)
P07 (m)	P16 (f)	P09 (f)	P27 (f)
P08 (m)	P17 (m)	P18 (m)	
P09 (f)	P09 (m)	P21 (f)	
P10 (m)	P18 (m)	P22 (f)	
P11 (m)	P19 (f)		
P12 (m)	P20 (m)	group 1: P04, P09	
	P21 (f)	group 2: P13, P21, P22	
	P22 (f)	group 3: P14, P03, P15	
	P23 (m)	group 4: P05, P18	

4.3.3.1 Workshop 1 – Focus Group "The Quantified Workplace". The focus group engaged twelve (12) occupants of a quantified building, to explore their values and perspectives on the collection and use of environmental and potentially personal health data in the context of a shared workspace. The discussion started with asking the participants what data are currently collected by the building and their use in the workplace at present, while showing the building’s WebGL(3D modelled) API (Figure 29). Based on their current experiences, participants addressed their views on data accessibility, useability and use, data control and privacy in the building. Participants further explored ideas about future use of data in the building for individual and collective health and wellbeing purposes, and the acceptability of other means to collect, process and use health and personal data in the workplace – e.g. using wearable and ambient sensors (Figure 28).

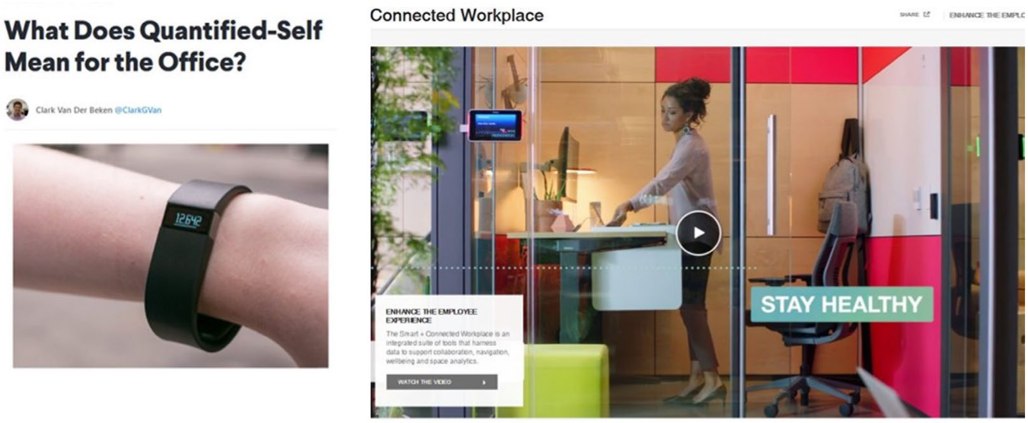

Figure 27: What Does Quantified Self mean for the Office? Wearable data and health. (Public domain). (https://robinpowered.com/blog/what-does-quantified-self-mean-for-the-office/).

4.3.3.2 Workshop 2 – Virtual Focus Group "Data Traces and Materiality" . Through a virtual presentation followed by a virtual focus group discussion, I introduced the idea that the buildings passively collect data and change over time as a response to human activity. Following S. Brand [10], buildings 'learn' from slow physical interactions with their

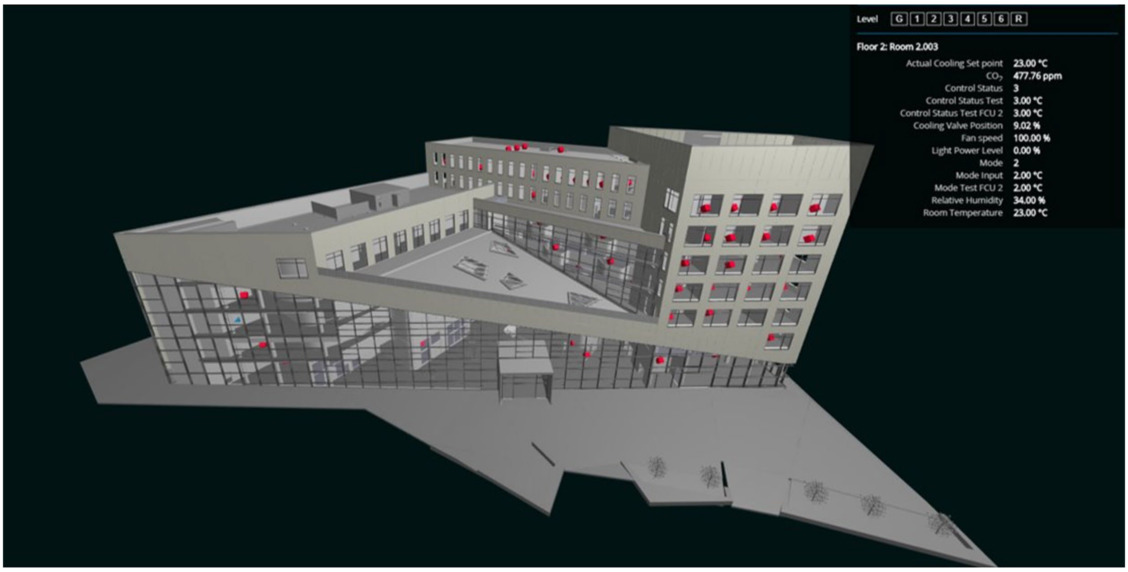

Figure 28: The building's API – data streaming.(Public domain) (https://3d.usb.urbanobservatory.ac.uk/). The Web interface shows the buildings 3D model and various data points in the building, which are click-able. Upon click, they show what types of data is collected in this specific area of the building, and the current measurements. In most building areas, the sensors are temperature, humidity, CO2 and occupancy.

occupants over time – e.g. modifications happening due to space use. Through an occupant-driven evolution of the built environment, he describes the buildings consisting of 'shearing' layers of change [10]: site, structure, skin, services, space plan and stuff; all with different temporal dimensions of change capacity [3]. In this workshop, smart buildings were be understood though the same theoretical lens; with the 'data' layer added [67] (Figure 30). Giving this theoretical framing and using the same smart building as an example, the discussion focused on processes of data layering – i.e. data accumulation, materialization and physicalization in the built environment over time. Physical analogies of data layering over time such as the patina and the palimpsest were presented as such examples to 15 participants (Figure 31). Participants were then asked to reflect upon long-term processes of data layering and materialization in the built environment, and the changing value of accumulated data in the short (1 week, 1 month, 6 months) and the long term (1 year, 10 years, 50 years).

4.3.3.3 Workshop 3 – Virtual Design Fiction and Group Story-telling activity "Future quantified buildings" . Ten (10) participants were engaged via Zoom, divided in 4 groups and were given access to a storytelling toolkit : a series of 360 environments featuring workspaces (office and domestic/home-office) (Figure 32), fictional characters, and a selection (palette) of embedded and wearable sensors. Using the toolkit, each group was asked to choose one character, immerse in one environment, and create a novel story that addresses the collection and use of data in the build environment over time. The activity was hosted in zoom (60'). It started with a brief introduction (5'), work in groups (zoom rooms -35') and concluded with group presentations reflecting the most interesting points of each story and the potential value of data for the users (20').

4.3.3.4 Workshop 4 – Online Design Fiction and Story-telling activity "Future data-driven Architectures" . Workshop 4 further explored topics addressed in previous activities focusing on the experiential, physical and material dimension of data use in the built environment; adding the concept of data reactivity/interactivity. Aim of the workshop was to explore the design of future adaptations and responses in the build environment. Seven (7) participants were provided with examples of adaptive architecture(s) (Figures 33, 34). They were asked to reflect on the forms of data that are required to build such environments, and the value of data for the users over time. The workshop concluded with a story-telling activity using the toolkit introduced in Workshop 3. For this last workshop, I used an embedded google form and a presentation hosted in GitHub pages. I provided a link to the participants to work individually and in their own time to allow in-depth thinking.

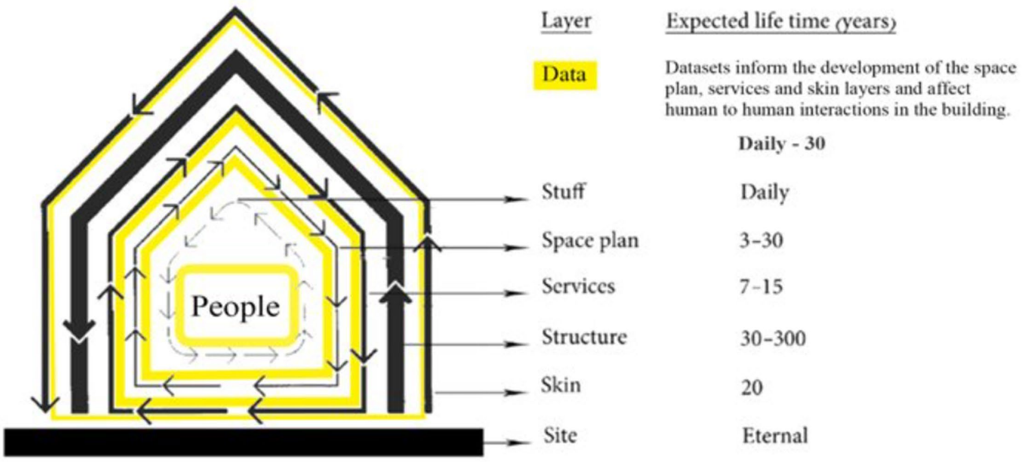

Figure 29: The Buildings as Layers and the role of Data and People. Picture modified by the researcher. (Public domain). (https://medium.com/@bhakti1711/how-buildings-learn-wip-619bd89e845e).

Figure 3130: Patina and Palimpsest analogies, data layering processes in the built environment over time. (presentation slide).

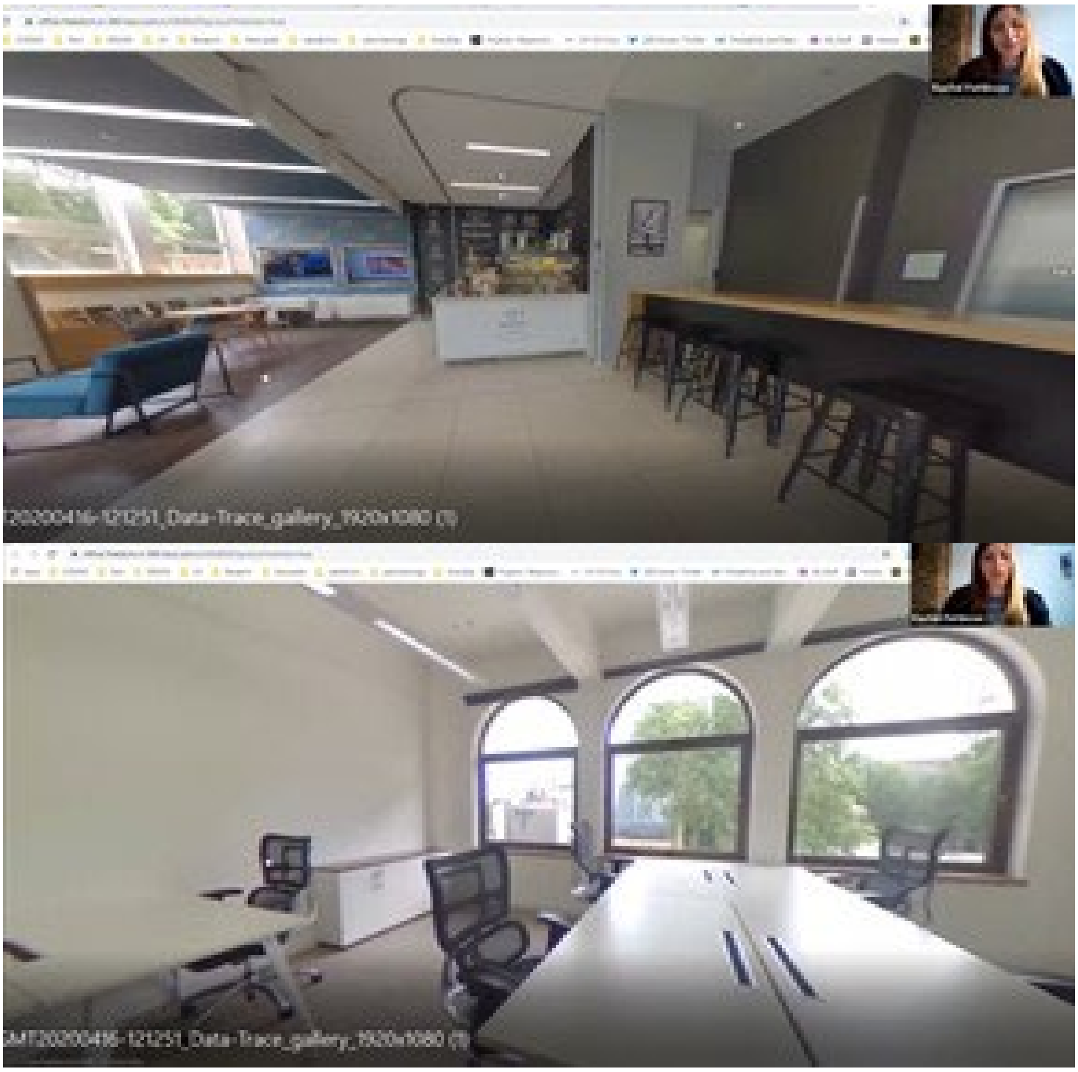

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Figure 31: Participant narrating their story at using 360 image of a workplace – lounge area (above) and desk area (below).(Zoom caption during activity)

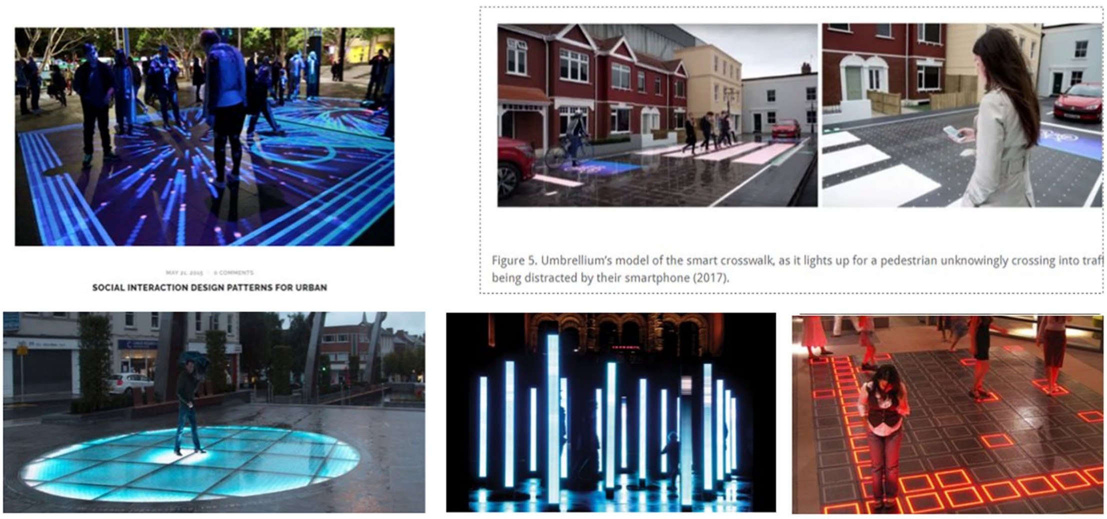


Figure 32: Interactive Architecture and Light (presentation slide).

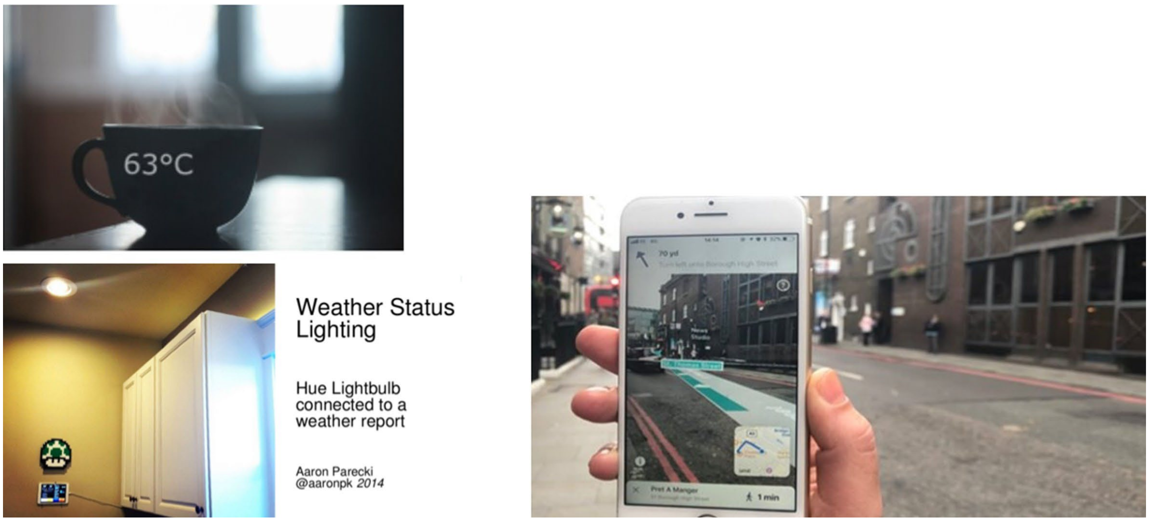


Figure 33: Ambient Interfaces and Built environment (presentation slide).

4.2.4. Data Collection and Analysis

All workshops were audio recorded with the participants' permission - those hosted in Zoom were also video recorded with the participants' consent. Audio recordings were transcribed by the lead researcher; the answers from google forms were exported in excel format and used as text. Transcriptions of all workshops were coded and subjected to thematic analysis [33,263]. I chose thematic analysis as the method to analyze collected data, as it allows flexibility and reflexivity when analyzing complex qualitative datasets. The data analysis procedure included selecting quotes from the data (codes), performing a group clustering session (first order themes) and then further clustering (second order themes). A reliability check was performed by the rest of the supervisory team, and repeating of the clustering process to finalize themes. Data was 'open coded' which entailed that data was clustered without a predefined elaborate coding scheme.

4.3. Findings

Thematic analysis suggested the following themes: 4.1 Data confusions, 4.2 Privacy Complexities, 4.3 Surfacing building data and making it useable 4.4 AI and health and wellbeing. I unpack these further below.

4.3.1. Data confusions: what data is collected and how, and is it personal?

Throughout discussions, confusions and concerns over the types of data collected were unveiled. Many participants expressed they are not aware what data is collected, what is the purpose of collection, if this data is personal or not and whether their consent should be given or not. *"Why do we need to capture all this? ... If you want to get a sense of how the building is then walk around." (P06 / S01). "This building is supposed to be highly monitoring but I'm not sure that I really understand exactly what and how is it monitoring and if we consented to." (P09 / S01).* A few participants insisted that their informed consent should be given for all data types that might relate to human activity in the building, even if this data is not inherently personal. *"Have we actually consented to have all our toilets monitored?" (P02 / S01).*

The above statements illustrate existing confusions over which types of data are personal and which are not, and they how they should be treated in relation to giving consent, giving room for more 'personal' interpretations of personal data. As the discussion evolved, it became clear that participants wanted a more nuanced agreement over what constituted personal data.*"I think it's important to clarify what data (is personal)...for examples I think if you access the admin and say: Give me my personal data from this building, excluding cards etc, they will say: there isn't any. I think we should be careful about what is what we call personal data" (P07 / S01).*

The discussions further explored what forms of data collection are perceived as appropriate and acceptable in shared spaces such as workplace buildings. Data obtained by ambient sensors are mostly perceived as unproblematic by many participants. *"I think all things (referring to temperature, occupancy, air quality) except for the video recordings feel quite alright, they sound quite anonymous." (P04 / S02).* This was contrasted however, with data that was more explicitly tied to individual activity. *"I am aware of examples where the smart card systems being used by line managers to track what time someone is coming in and out of the building. That's definitely not acceptable." (P02 / S01).*

That being said however, the term 'passive data' emerged in some of these discussions, referring to data on secondary effects of human activity. Passive data was mostly related to collecting data after an action or human activity has happened – e.g. using sensory devices or qualitative observation and excluding any human subjects involved. Such data was perceived to be inherently privacy-friendly, highlighting the importance of the temporal dimension of data collection practices. *"You could infer the use of taps from the sound of water coming on and off on the pipes, which I thought was a neat way of collecting data without having to actually use any consents" (P02 / S01). "Monitoring secondary effects of human activity can preserve anonymity while providing data about peoples' preferred ways of using the space." (P15 / S02)*. A few said passive data can be real time – e.g. data from ambient sensors as suggested above – as long as users are not actively monitored. As this didn't exclude disclosures that might come from combining different data streams, this view remained questionable among some participants.

4.3.2. Privacy Complexities: Scale of data and perceptions of privacy

Participants' interpretations of privacy were further influenced by ideas of scale, across a number of dimensions. These dimensions included physical size (from person to workspace to building); the pace and frequency of data collection (e.g. continuous versus sporadic data collection); and form of data processing – e.g. data aggregation, combining data streams etc. These were all ways in which scale of data could be modified and had attendant impacts on perceptions of privacy or intrusiveness.

Thinking first about physical scale, it is evident that the scale of a desk is perceived differently from the scale of a room in terms of privacy and acceptability of data collection practices - e.g. occupancy sensors at each employee's desk in a shared office space can be privacy threatening, whereas the same data collection method in large meeting room poses less of a threat. *"I think if the outcome is having my individual office being monitored that's different, like, a meeting room. It's useful to know which meetings are in use and which are not, but then if I'm being tracked in my office, then that's a different response." (P05 / S01)*.

Data collection at small scale also requires a different set of interventions due to potential privacy loss from combining different data streams. Participants expressed concerns over compromising privacy as a result of data localization and contextualization – e.g. combining occupancy sensory data with organizational data.

"Well it is not personal data down here, roughly because there's, for every given sensor area, there's maybe five or 10 desks but go up to the sixth floor: almost everyone has one at their office. So, where does that boundary end? What happens if you have four people in an office and some of them only work part time, they become identifiable." (P02 / S01).

Continuous monitoring also raised concerns relevant with the perceived privacy of individuals. It created mixed feelings, with some highlighting the importance to collect as much data as necessary, at the points that are necessary, for the purpose necessary. *"It's more about specific applications of things at places needed - ensuring that you, for example, have a sense of 'safe lifting', that's very different than heart rate monitoring all the times - although both can be used to measure the same thing." (P01 / S01)*.

Regarding the broader concerns over privacy loss, some participants argued that if the value of data use is distinct and desirable for the individual, it could compensate with potential privacy loss. Others stated that there should not be any trade-off between value and privacy: *"I don't mind giving my personal data away if I'm going to benefit from it." (P05 / S02). "It shouldn't necessarily be that trade-off between privacy and usefulness. And privacy by design means that you can have high functionality without surrendering your data" (P03 / S02)*.

Data aggregation came across throughout discussions as a process that appeals to privacy concerns of many participants. Data aggregation in the built environment has different dimensions; participants mentioned spatial dimensions and the use of varied types of data. *"In aggregate, we're not talking just about is it like an individual office versus a large open space where there's lots of people; That's one form of aggregation, but what about aggregation and lots of different types of data." (P02 / S01).*

Aggregation as a dataset conceptually appeals to privacy concerns of many participants. Aggregated data was seen as privacy - friendly enough to be used in public to raise awareness around collective behaviors and to direct organizational responses. *"A lot of it for me is about whether data is aggregated or not. ... If it is aggregated data then, although it might be possible to identify me from that, it takes a significant more amount of effort to do that at the very least." (P01 / S01). "If you do it in a way that is aggregated, so for example, it only signals when heart rates become above a certain level. And they would only transmit this kind of data at the end* *of the week as an 'overview statistics' ... the organizational body could never really track individuals based on that." (P04 / S01).*

4.3.3. Surfacing building data and making it usable

Many participants expressed the view that although a lot of data is collected in the building, they do not see or feel how it is utilized in any (beneficial) way (data capture effectively takes from them, without giving anything back). For example, the building collects but does not act or respond based on the collected datasets in ways that may improve occupants' wellbeing and their daily experiences in it. *"A very different point but taking that it's a smart building; I'm actually a bit disappointed, because I feel like they are only measuring but I don't see any evidence of the data being used for or for maybe for environmental reasons, or well-being. ... It doesn't sound like or feel like a smart building to me." (P04 / S01).*

The points below illustrate the perceived underutilization of collected data, but also the lack of infrastructure that can create awareness on data collected, and meaningful experiences in the building. Mentioning air-quality levels in the building, participants referred to how their senses help them become aware of potential problems, rather than the sensory data. *"For example, you can't really see but you feel the oxygen level drop over the day in the lab, you really feel like you get more tired. If they could do something about that using the sensors, they just pumped some air in or whatever, do something about it, but they don't." (P04 / S01). "When there was a gas leak, they found out because of its smell not because of the sensors." (P05 / S01)*.

Focusing on existing visualizations of the buildings' data (through the associated API), participants mentioned that it is rather hard to read and make sense of. Although the data is openly available, it is not accessible and useable by the average user. As highlighted below, what is missing are the tools to enable users make sense of it and use it in a meaningful way. *"It's just an output more or less of like raw data. And there's a certain level of interference that's kind of missing that to make the data useful to somebody who's not a visualization specialist or something." (P03 / S01).*

Participants agreed that surfacing collected data to create awareness could transform their experiences in the building. There were some ideas on how this could be done through data visualizations and physicalizations. Key ideas were surfacing environmental and occupancy data, free movement in the building; and technologies that allow the building occupants to become aware, experience data, and use it as they feel it's meaningful. *"A thing that can be useful is providing ways to surface that information and just letting people use it how they would see it fits. So noise case, for example, if you could easily see, you know, what was currently the quietest space to work, then you could take yourself there ... almost like doing a Google search in the building for noise and then being like, I'll just go to that space etc." (P01 / S01).*

For some participants, simply having more interoperable data can generate value as it becomes easier to analyze and use; for others however, there was a feeling that the value of data capture would be raised by exploring how the building supports the occupants to be smarter, and take collective action. A central idea among proposed use-cases of data was the need to empower the building occupants through giving them more control for example, over using data, as part of a lightweight infrastructure within the buildings. *"Our conception of the 'smart' building lies entirely in the inbuilt data and information networks that a building contains, with a view to managing its energy use. ... (this) is a limited vision, and that perhaps smartness should come from the occupants, rather than the environment." (P25 / S04).*

Participants proposed that processing accumulated data – e.g. as environmental and usage data, movement data – could help users develop awareness about their own behaviors in the buildings and support smart decisions at an individual and collective level on how they use and manage the built environment. *"The many measurements that are made in the office space are also synthesised into an app that employees can use to find their favorite places in the office ...one month after the new office space has come into use and the app has collected enough data to inform you about your preferred usage patterns of the building." (P04 / S03).*

It was also postulated by participants that there is an inherent long-term value to building data. It was suggested that accumulated datasets could be used for the systematic study of usage patterns in buildings to inform user-centered building design and adaptation, and space management, by directly learning from other occupants' past and present activities, and the application of collective analytics.*"... when I think of value, I first think how to optimize, but it might be valuable to know how other people have configured their rooms or desks, and where they've spent most of the time ... It would be valuable if you could sort of see that it in a different way, and optimize how your space is configured." (P14 / S02).* However, intriguingly it should be remembered, as one participant suggested: *"I think, the sort of main argument around smart cities or against smart cities, is that a city is not all about optimization."(P03 / S02)*. Therefore, thinking about how data can support value-added activity beyond this is valuable. The previous quote suggesting using data not necessarily to optimize space use but to reveal potential for reconfiguration and re-use. It was also clear that the participants also understood there to be a social contract one might enter in to around the collection of data, which was in essence for the greater good, and for which short-term sacrifice of privacy might lend itself to longer term utility.

"(about smart offices and energy footprint) It means of you giving out some data because you enter some things in your phone, and probably your home collects some data about your behavior, but I think if you scale it up, and if you consider this in the long-term perspective, it can have a very valuable impact to society." (P15 / S02).

4.3.4. AI, control and health & wellbeing

In many fictional narratives, the perceived value of data was highly linked with supporting health and wellbeing – e.g. buildings as restorative spaces. The concept of environments that learn to adapt to their users over time based on accumulated & processed environmental, occupancy and health data came across in many of participants' narratives. Other ideas included managing environmental comfort, microclimate and task distribution in the building based on data. *"Responsive room ... that can adapt to emotional states based on physiological data and environmental data that is collected. ... It can also do spatial adjustments depending on the number of people in the room." (P24 / S04). "The work environments could measure how much specific desk area was used and whether it had light there ... Maybe there should be a change in how these desks are being used based on data ... to better adapt it based on kinds of tasks and light." (P04 / S03).*

The fictional narratives were particularly rich in demonstrating different perceptions of agency and control in adaptive environments, as well as the long-term consequences of AI training on accumulated data. Control is often shifted from the building occupants as the building is now responsible for managing their wellbeing and activities in the building. Sometimes users are aware and are given options to control what the environment is doing, in other cases the changes happen subtly and without awareness. *"Adaptive environments can learn over time what settings are most effective e.g. increase temperature or change oxygen concentrations. It can learn what lighting changes are most effective to calm people." (P04 / S03). "The room reads body temperature, heartbeat, pitch of voice in additional to environmental data such room temperature, noise levels and light. Based on this data, the room adapts by offering a range of lighting options (including control of window shades), soothing music when stressed and regulates the room temperature depending on if it is too hot or too cold. (P24 / S04)*

Conversely, concerns of being controlled or manipulated by the environment based on collected health data were reflected in both utopian and dystopian scenarios- e.g. the building taking over control by imposing specific changes without the occupants' awareness and desire. *"Maybe the room would start to influence us, if we were reading or sleeping too long it would disturb us to do something different." (P26 / S04). "Maybe the room could do more to adapt to our mood and/or activity and support us in what we were doing - partying, reading, sleeping, eating etc. If we were sitting quietly the lights could dim, the walls could become soft in some way. If we were moving around, the lights could be bright, windows and curtains open. The issue might be that the environment starts to control us, or we start acting in an unnatural way to provoke a change in the environment." (P27 / S04).*

Finally, concerns on data reliability came across in both discussions and story-telling activities when addressing health in the built environment. *"But is data reliable? Is the data valid in terms of measuring what we think it is measuring, and is it meaningful? I'm reluctant to rely too heavily on quantified data without a better understanding of the issues." (P02 / S01). "Does anyone track their sleep? Sometimes you wake up in the morning and you feel like you had a terrible night, you feel really tired and your data tells you slept perfectly well...My boss was coming to my desk and saying you are really stressed...and you are not! Or if you are really suffering and the computer says no." (P10 / S01). "There's the flip side as well, you go to* *occupational health because you just feeling really stressed and anxiety, anxious. And the computer says, no you are fine." (P06 / S01).*

These concerns also support the view that the use of data should support and not replace human agency, which returns us to the previous section and the argument for using data to support smarter occupants not smart buildings. *"I think the danger is if that data is used as a replacement for human interactions which is about care and well-being... they should support and not replace" (P06 / S01).*

4.4. Discussion

This research chapter explored occupants' experiences in quantified buildings following an exploratory, qualitative approach, responding to:

- **RQ1:** What are the experiences of the building occupants in the quantified workplace? (RQ1a: What are the experiences of the building occupants of a quantified (smart) office building?) and
- **RQ2:** How do their experiences inform data use for wellbeing in the buildings for work (RQ2a: How do they view data collection and use for health & wellbeing in the building?)

In the following section, I will unpack some thoughts about the implications of these findings for future research and the design of occupant-centered quantified environments. Based on the above findings, I provide recommendations for improving privacy in current data-rich workplaces. Moreover, I propose design directions for increasing the perceivability, accessibility and usability of data in quantified buildings; and particularly the use of data for health and wellbeing. Finally, highlighting pressing research challenges for the occupant-centered development of quantified buildings; I propose key considerations for a broader design research agenda for smart office buildings.

Albeit speculative, the findings highlight pressing issues in quantified buildings, existing opportunities for data use for their occupants and design opportunities herein. Based on these results, I have gone on to further prototype an interface to foreground the data to the building occupants; which is the core contribution of design research Chapters 7 and 8. However, the reporting of the design and evaluation of this interface is beyond the scope of this chapter.

4.4.1. Situated / in-place systems for data awareness and use (RQ1)

The analysis has shown that there is a need to support a more pro-active approach [313] to how the built environment responds to collected data, encouraging actuations to take place and engaging users in experiencing and interacting with that data [114,156,277]. Surfacing data at physical scale creates different dynamics [114,148,290,315,394]; awareness technologies in the buildings [4,35,167,315,394] can bring latent aspects in the foreground of human experience– e.g. an example is where participants refer to being able to smell, see or feel changes in air quality instead of just collecting data about it [20,41,153,172,204,226].

Examples of such data physicalizations for awareness include the recent work on atmospheric interfaces [41] crafting a space for the development of novel ambient interactions around air quality.

More broadly, there are potentials for the design space of physical interfaces such as e-textiles, shape changing, haptics etc. [41,153,243,246], to contribute to a physical and experiential agenda for smart buildings [172], creating applications at variable scales [204] - e.g. furniture, interior spaces, façade systems. Scale can have a greater impact [204,315] in raising awareness on environmental aspects – e.g. air quality, energy use - as well as aspects of the collective life in the buildings – e.g. use of space. Beyond the many examples of relevant past works [14,153,169,289,326], there is space for expanding the design agenda through exploring potentials of physical interfaces and interactive materials at scale in the buildings [204,243,246]. Apart from physical scale of actuations, temporal scale of data feedback in the built environment has not been adequately explored [32,265,266,421] – e.g. actuations that happen slowly, in an organic way; material changes that display data over time etc.- providing opportunities for feedback that does not monopolize attention [23,148,206,313,373], and makes users think [48,156,313]. Examples such Organic UIs [246,274] and slow HCI [140,206,226,265] illustrate some of the attempts towards that direction, reinforcing a smart building agenda where smartness comes from the occupants and facilitating the ways in which they might respond to data, and not from a building's data management system [231].

Beyond awareness, the findings highlighted the importance of data accessibility and use; the need for interventions that leave space for users to control how to use the data. Participants suggested the development of lightweight tools for open use of collected data by the occupants; shifting the control on data use from the building to its users. Improving data accessibility creates opportunities for levelling control [108,124] of the use of data, reinforcing an agenda of smart buildings that have potentially 'DIY' and 'open-source' dimensions [48,61]. There is therefore room to design for spatial accessibility of data, providing opportunities for building occupants to engage with and use data in the buildings as they think it is meaningful [156,422,423].

Summarizing, the value of data for the participants was linked to its ability to be experienced, to be made perceivable (raising awareness of data) and for it to be openly used by occupants as they think it's valuable. Different forms of data physicalizations and foregrounding of information can encourage a more proactive engagement in the building's use of data by "turning control to the users" [108,124], transferring the responsibility and choice of action from the smart building to support smarter occupants [108,313,317]. Not only is the accessibility of data highlighted, but the ability of users to meaningfully interact with it [156,422,423]. Such engagement techniques can empower occupant's control in the quantified buildings, while having a tangible and/or visible value and positive impact of the use of data on their daily experiences.

4.4.2. *Designing for a constantly negotiated privacy (RQ1)*

My analysis unveiled some of the existing confusions regarding data collection, what personal data is in quantified buildings, and whether consent should be given for collecting data. Participants' views on personal data varied, illustrating the fact that such environments have many complexities around privacy-friendly data collection. The above analysis also illustrated the underlying discrepancy between the perceived levels of privacy and the actual privacy [193,251,260]. Reflecting the work of Nissenbaum on privacy as contextual integrity [260], this work illustrates that physical scale and architectural factors impact perceived privacy [251,257] and determine what forms of data collection and data types are perceived as acceptable [5,133,420]. Moreover, it advocates that physical scale can potentially have an impact in actual privacy, illustrating the mismatch between current policy and the realities of lived-in smart buildings [207].

Besides physical scale, proportionality and scale (e.g. mass) of data collection was addressed as a privacy-determining factor -e.g. requests for data minimization – which is also left vaguely interpretable. The idea of the continuous monitoring and the massive datasets that are produced were related with potential loss of privacy. Participants addressed the importance of only collecting as much data as necessary, at the points that are necessary, for the necessary purpose, highlighting the importance of application - specific collection of data [193].

Past work on privacy and data collection in smart environments illustrates some of these problems [260]. As a result of the mismatch between physical and digital boundaries in quantified buildings, privacy is perceived as fluid in quantified buildings, and in a dynamic relation to architectural and social factors [260]. Perceived privacy is a proposition to be negotiated and contested, evolving, and changing throughout spatiotemporal scales. Any user-centered design solutions that are developed in that space therefore must consider the effects of spatiotemporal relationships on perceived privacy. This urge for a more architectural and physical design for privacy promotes embodied awareness [99,207,284,392] and tangible control mechanisms [5,392].

Of note, GDPR [112] regulations (of critical importance to those of us living and researching in Europe) do not address any of the above concerns; principles such as the meaningful consent, data aggregation, data minimization and anonymization as mentioned in GDPR are general guidelines, with their application in the built environment creating complexities. GDPR cannot take spatiotemporal relationships and physical boundaries into account. This also leaves space for concerns and misinterpretations. There is also a difficulty of nuance, with individuals having variable and contextualized understandings of acceptability over matters of privacy and the use of personal data, and this creates extensive difficulties in translating privacy into a global building GDPR policy or architecture. These difficulties are inherent to the sphere of privacy in quantified buildings and therefore encourage design-led and context-specific interventions.

[112] https://ico.org.uk/media/for-organisations/guide-to-the-general-data-protection-regulation-gdpr-1-0.pdf

Our work illustrates that users have concrete expectations regarding how buildings function that have been well shaped by the years of making and inhabiting them [32]; and diverse expectations on what and how data in the buildings should or should not be used in the context [251,260]. Data in buildings can be perceived as yet another 'shearing' layer [32] that represents a complex space of activity within a building, but it is not commonly seen as an inherent infrastructural 'utility' layer such as electricity, ventilation or plumbing. Thinking about data and occupants' experience of it as another layer of building fabric, and as a physical/material element in buildings (e.g. data materialities) [14,20,156,172] could potentially shift some of the problems around perceived data privacy and acceptability. In that sense, having a GDPR-first approach when addressing data in buildings can lead to a deadlock, whereas prioritizing data materialization and usability through user engagement can potentially allow different perceptions to evolve.

Overall, there is a need to clarify and inform the regulatory framing of personal data and privacy within the quantified built environment, and the processes through these regulations are applied in each context, prioritizing user engagement and data use. Within that space, there is potential for design research in quantified workplaces to accommodate a physical design that allows negotiating privacy in different levels; designing technologies that allow a more 'dynamic, user-centered and tangible privacy' [5,392]. Moving forward towards 'privacy -by- design' quantified environments [193,257], buildings should prioritize making occupants aware of data collection taking place and allow them to 'level their privacy' – e.g. filtering the sharing of data depending on where they are (physical scale and spatial attributes) and the tasks they are performing (e.g. uses of space). This will likely require the development of appropriate socio-digital-architectural design patterns – which can be easily deployed by both building designers and building managers. Such design interventions should enhance both the perceived and actual privacy of the building occupants. Examples of such artifacts could be interactive room dividers that help users control and customize both physical and digital boundaries at the workplace; that enhance awareness on data collection through physical feedback – e.g. material color change, light notifications - and provide tangible ways for users to control the amount and pace of data collected in the building's spaces they inhabit – e.g. touch to control pace of data collection, data accuracy, or appropriate data streams.

4.4.3. Rethinking smartness: Designing for the collective and the long term (RQ1)

The value of accumulated data in the long-term was related to data on collective use patterns of the built environment, used to inform present and future building design and management. As participants mentioned, the study of intuitive spatial use patterns can be systematized through data collection and inform future designs of adaptive architectures [169,329,331,374,404]. Data accumulation can provide insights and design directions based on the collective, 'informal' and 'unplanned' uses of space and the 'organic', 'intuitive' and 'slow' adaptation processes that happen in the built environment by its occupants' activities [32,140,143,209,265,326], providing novel solutions to contemporary problems about how buildings can be better designed and built for user-centered patterns of use.

Collective analytics – i.e. open datasets produced through collective engagement in the buildings that are openly available for collective use – can provide new insights on how 'smartness' can be driven by the building's occupants and not the building's infrastructure. Surfacing' or 'layering' these datasets through lightweight infrastructure that allow collective control on data use could radically change how the building occupants perceive and use quantified buildings. The process could be described as a passive long-term adaptation of both people and environments [32,143] – a symbiotic process of co-adaptation - based on iterative interactions with data in the prospect of serving broader societal and environmental values, such as reducing the buildings' energy footprint [27,70,89,337]. Critical to this, however, is determining who has the right to set the agenda for those societal and environmental goals to which the built environment is then shaping human behavior.

At the moment there is very little consideration of how collective behavior can actually shape the 'agenda' for a smart building – something that should perhaps be explored much further and which might fruitfully bring the research areas of 'Digital Civics' and HBI together.

4.4.4. Adaptive Environments for health & wellbeing (RQ2)

Occupants expressed conflicting insights regarding control and use of data for health and wellbeing from the built environment. Occupants discussed the undesirable effects in adaptive environments whereby their health and behavior is managed - and in some cases controlled – by AI, with or without their awareness, giving buildings themselves a new kind of agency. Although participants expressed that a level of automation in the buildings' response for wellbeing purposes would be desirable, awareness and the levelling of control of AI actions are again key considerations. As a few suggested, data should support and not replace any decisions around health and wellbeing in quantified buildings; pointing towards a more data-for-awareness approach, and transparency in the choice-of-action.

The above conflicts between the perceived value of data use, agency and AI control in the built environment can inspire researchers, architects and developers towards re-thinking and designing for human-driven AI in quantified buildings with a focus on health and wellbeing. Reflecting on the work of Urquhart et al., Schnädelbach et al., and Jäger et al. [169,329,331,374,404] on adaptative architecture, and the idea of human-building-collaboration by Rosenberg & Tsamis [317], the future of intelligent environments lies in developing interactive applications that embrace a full-body interaction with a building – i.e. using different forms of embodied actuations - and establish a collaboration between AI in the buildings and their users through feedback iterations [317].

Quantified environments could develop intelligent behaviors based on long-term iterative interactions -e.g. feedback loops - with their users to support health and wellbeing, whilst allowing users to control data use and actions initiated by the environments. Extending this to health and wellbeing agenda, the design agenda of restorative environments [353,424] has the potential to obtain a more human-AI collaborative approach, whilst enhancing behavior awareness to empower human agency.

4.4.5. Key Takeaways: a new design research agenda (RQ1, RQ2)

By exploring with building occupants their experiences of, and expectations around, a 'quantified' smart building, I have brought to the fore a number of tensions and concerns, in particular around privacy and data awareness or use, and shown how they can be nuanced in relation to spatiotemporal issues. At various points in the discussion above I have articulated some potential areas for further inquiry, some challenges that are then raised by these experiences which might help us set the agenda for future research in this space. Of course, some work has already been done to highlight agenda for HBI [143,332,374], but here with a specific focus on lived-in quantified buildings and design interventions, there are several observable areas of future work which could be fruitfully explored:

- Enhanced building privacy tools; Embedded/physical interfaces within the built environment could allow flexible, continuous monitoring of occupant privacy that shows the spatially mediated impact of data collection. This necessarily includes -
  - New tools for negotiating opt-in and opt-out possibilities for data sharing;
  - Interfaces that demonstrate the collective impact and value of data sharing;
  - Development (and evaluation) of privacy levelling socio-digital-architectural design patterns;
- New interfaces and 'information surfacing techniques' for data visualization and physicalization, to make tangible the live operational data in the built environment for occupants;
- Interfaces for temporal data interactions which highlight the aggregated patterns of activity in a building of 'slow' adaptation;
- Interfaces which support behavior awareness and health & wellbeing through feedback, which can actively explore the edges between environmental determinism and occupant agency;
- Interfaces for collective data use that incorporate different levels of user control.

Through these various proposed strands of research agenda – a potential new research landscape emerges that helps to better define an occupant-centered approach to smart buildings. Taking such an approach even in this limited study has already started to unpack some of the complexities around how issues of privacy might need to be dealt with in future and the challenges around supporting occupants' desired sense of agency in the face of automated environments. With a renewed call for exploring the human-experience of smart buildings there is much potential for developing new, engaging and ultimately occupant-centered data-interactions within the built environment, and hopefully this work helps to scaffold future work in this area.

4.5. Limitations

As mentioned above, this research has a number of limitations, particularly with regards to methods and scalability of findings. Participants' recruitment was based on the premise that they have spent enough time in the building to form lived-in experiences and expectations, and they were engaged for that matter. Some workshops had to be remote; participants were out of context which imposed challenges on unpacking lived-in experiences, and tools such as the 360 environments served to provide that missing link with the spatial context. As a result, the generalizability of the results to other smart buildings has its limitations; but as it is hard to access lived-in smart office buildings and their communities, this work offers a valuable contribution.

It is important to note that the above results are speculative in nature and this research exploratory; meaning that its purpose is to unpack subjective experiences and open the design space for a given problem and not to validate a specific hypothesis or claim the axiomatic generalizability of these results to any similar context. Although this can be the case – i.e. results can be broadly generalizable but need to be further validated - it is not essential to account for the credibility of this work. Given the exploratory and speculative nature of this research, these are inherent limitations of this work.

Another potential limitation of this work relates with the reality that the participants were exposed to, but did not directly interact with, the actual data of the building itself. One of the reasons was that the nature of the data collected being spatially localized to areas within the building meant that many occupants who worked in open plan spaces, would actually find it hard to map data to individual activity. Additionally, due to COVID-19, all activities turned to remote; tools needed to be invented to provide participants with a spatial context, and the potential localization of building's data was further hindered. It was therefore not possible to accurately foreground the data to the building occupants in a meaningful way, and there was also no actual interface for them to do this. I therefore chose to follow a speculative approach to unpack what to do with data if it was more foregrounded to the building occupants.

4.6. Conclusions

This chapter has presented one of the first explorations of occupants' experiences and expectations of a lived-in 'quantified' smart office building. This research specifically addressed the human dimensions of working (and to some extent living) within lived-in smart office buildings. Such environments will only increase in prevalence over the coming years, highlighting the relevance and contribution of this work. approach was exploratory and qualitative as befits an inquiry focusing on human-experience. The analysis highlighted existing research 'grey zones' around perceptions of privacy in such places, and emerging concerns and opportunities around data collection and use for health and wellbeing, and beyond. It has provided further nuance around design considerations of digitally mediated privacy and distilled broader design avenues for data awareness and use in occupant-centered quantified buildings. Such an approach will hopefully ameliorate the worst excesses of a potential slide towards techno-centric environments and will help to support more beneficial data-rich relationships between occupants and the built environment.

4.7. What is Next

The next chapter continues unpacking the experiences of the building occupants around quantification in and of the workplace; by focusing on the domestic workplace and remote working. The domestic workplace has very different dynamics; similarly, data acquisition and use at home while working is experienced in a radically different way. Apart from data-relationships and data-experiences in spatial context (that of the domestic office) (RQ1); the next chapter further explores dimensions of wellbeing as they are experienced by remote workers while working from home (RQ2). The choice of methods and format of the study presented in the upcoming chapter again aligns with broader constraints and considerations as they evolved during the time that the study took place; similarly, wellbeing concerns became more significant during that time. These two first empirical chapters provide the core basis of foregrounding experiences of data in place in two different contexts – office and domestic office – to guide design research that addresses quantification and wellbeing in both contexts; with the third empirical chapter attempting a data-triangulation or the bridging of these two separate research entities.

Chapter 5. Mapping the experiences of building occupants while working from home.

5.1. Introduction

While the previous chapter addresses the *quantification of* the workplace by focusing on smart office buildings and to data collection mostly through embedded building sensors; this chapter addresses the quantification in the workplace, focusing on the domestic workplace and the collection and use of personal and health data collected primarily through wearable sensors. Addressing relevant gaps within HCI and HBI research on the domestic workplace; my research aim in this chapter is to map aspects of the data and wellbeing experiences of the building occupants while working from home. Responding to RQ1 and RQ2, in this chapter I present and discuss findings from an exploratory diary study during COVID-19 lockdown (during a period of exclusive home-working) with 13 participants - many of them employees of the same shared workplace building - for a period of 4 weeks. The results frame an understanding of occupants physical & data experiences while working from home, such as a) people's engagement with physical (i.e. spaces, making a home office) and ambient aspects (i.e. perceived environment& microclimate) of the lived-in domestic workplace, b) their experiences with data collection (self-tracking) in the domestic workplace for wellbeing purposes, c) the broader challenges raised for their wellbeing while working at home and d) the opportunities for data use (data feedback) to support wellbeing.

5.1.1. Research Context

Over the last three decades there has been increasing interest in supporting more flexible working[176,181], which has seen the rise of the 'home office' and 'remote workers' [105]. This has particularly come to the fore during the global COVID-19 pandemic, which has both forced people to work from home, but also increased discussion of the possible values of the domestic workplace post-pandemic [183]. COVID-19 has also boosted quantification of the workplace [98]; particularly giving rise to use of self-tracking technologies for monitoring health and wellbeing while working from home [47,98,210,316]. Within this context, there is limited research on the experiences of home workers – regarding both their experiences engaging with the physical space and data in it. Most of the past research on the workplace focuses on office buildings [9,10,16,70,114,195,218,422]; with extensive studies concerning the potential role of digital technology in supporting the well-being of office workers – see, for example,[206]. Recently there has been an emerging academic discourse around Human-Building Interaction (HBI) [142,143,332], and some of this crosses-over into discussion of workplaces and the wellbeing of occupants [206,228,308,349,350,353]. However, this leaves prominent research gaps in understanding quantification in the domestic workplace for wellbeing, and the experiences of the building occupants in that context.

5.1.2. Research Questions

Addressing the above research gaps, this chapter responds to RQ1 (RQ1b) and RQ2(RQ2b):

- RQ1: What are the experiences of the building occupants in the quantified workplace? (RQ1b: What are the experiences of the building occupants while working from home? and
- RQ2: How do their experiences inform data use for wellbeing in the buildings for work (RQ2b: How do they experience data for wellbeing when working from home?)

To address existing research gaps and respond to the research questions above, I conducted an exploratory diary study during COVID-19 lockdown (during a period of exclusive home-working) with 13 participants - many of them employees of the same workplace building - for a period of 4 weeks. The study maps aspects of the physical and data experiences of the building occupants while working from home; involving both qualitative and quantitative measures (mixed-methods approach). Following a pragmatic methodological lens, the study design, set up and choice of methods was heavily influenced by lockdowns, imposing remote work and remote engagement with participants. The framing of this study under the concept of the 'quantified self' (self-tracking) [98,210,316] in the buildings for work, allowed generating datasets using wearable devices following a non-interventionist approach to data collection. Tools to achieve data collection included commodity sensor wristbands, and a custom web application for self-reporting wellbeing and aspects of the environment while working from home. Tools to achieve data collection included sensor wristbands, and a custom web application for self-reporting wellbeing and aspects of the environment while working from home.

5.1.3. Research Contributions

Based on the analysis of both the quantitative and qualitative data, this chapter unpacks aspects of the physical engagement with the home office, the wellbeing challenges of the domestic workplace, establishes correlations between self-reported wellbeing and perceived environmental aspects, and discusses the impact of data use to support wellbeing of remote workers. Insights from these observations are then used to inform design research. Similarly to Chapter 4, this chapter concludes with a design research agenda tailored to the needs of the domestic workplace and with potential applications to both shared and hybrid workplace; addressing data use for health and wellbeing in a dynamically changing workplace and the specific design opportunities for ambient interventions in domestic workspaces. Framing it as the 'ambient workspaces' design agenda; it provides directions for design research on ambient technology to support wellbeing at a spatially distributed workplace- here with an emphasis on the home office – and showcases three possible design interventions. Drawing upon the research fields of Ambient Intelligence[4,23,45,75,299,315], Human Building Interaction [142,317,332,374,404] and Human-AI interaction [11,423] in the built environment; key aspects of 'ambient workspaces' agenda are the idea that the physical space – or the buildings

– are an important player in supporting or inhibiting wellbeing, and that data use should support awareness through physical, material and ambient interactions in the buildings.

Summarizing, this chapter has empirical and design contributions to the field of Human Building Interaction research, providing (1) a detailed understanding (both qualitative and quantitative) of the physical and data experiences of home-workers; (2) a future design agenda for 'ambient workspaces'; and (3) three design concepts illustrating ambient feedback and data use for wellbeing, to illustrate the utility of this design agenda.

5.2. Methods

5.2.1. Study Set Up

The study engaged 13 participants for a period of 4 weeks during June-July-August 2020. The participants were posted a wearable band (Mi Band 2) measuring a) the type of physical activity – cycling, walking, running, b) step count and distance, c) heart rate data and d) sleep data (if worn while sleeping). They were asked to wear the band during the whole study period – preferably 24/7, or at least during their working hours. The participants also received a daily email with a link to a purpose-built static web app (see Figure 35). The app offered an easy-to-use interface for documenting aspects of their wellbeing and to characterize the individual workplaces using sliders, text input fields (diary entries) and image uploads. In terms of providing a measure for wellbeing, dimensions of the Circumplex model of Affect were used in the form of sliders (more information in following section). The participants were asked to upload a picture of their workspace (home office), evaluate their surroundings/environment and aspects of their wellbeing using the sliders, and fill in a short diary for that day. The email was sent either in the midday break (at 12:00) or at the end of workday (at 17:00) in alternate; aiming to create a pleasant 'routinely variation' that the participants expected without interrupting them during their work. Depending on the time sent, dedicated questions were asked via the app to trigger either 'on the spot' awareness- i.e. where are you working now? how do you feel now? - or self-reflection of participants - i.e. how has your workday been? Besides their daily feedback via the app, participants provided the researchers with the wearable's data - heart rate, physical activity (type, steps & distance), sleep (if any) - at the end of the 4-week study period. Participants were also interviewed (30' semi-structured interviews via zoom) after the end of their enrollment, to reflect on their overall experience of the study and the technologies used.

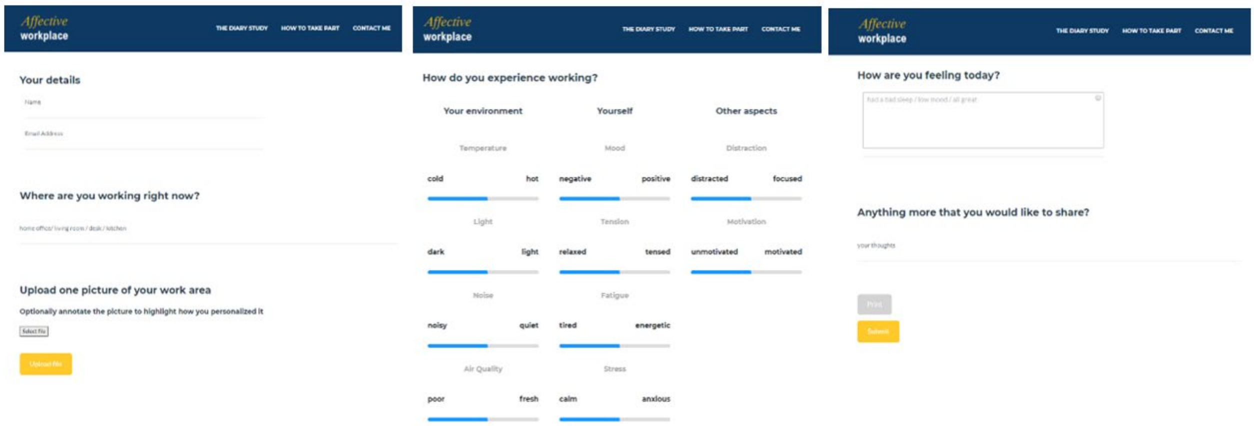


Figure 34: The web app interface

5.2.2. Participants

The 13 participants (see **Table 03**) were recruited via social media (Twitter, Facebook). The recruitment purposefully targeted knowledge workers as they were more likely to be working fully remotely (and not partly on-site); and they would potentially be more experienced in remote-work (also prior-lockdowns) – something that would support generalizability of findings beyond COVID-19. As knowledge workers, they were highly educated – which is a naturally derived limitation for this study. Their educational background varied, coming from research, software, design, and psychology sectors; and ranged from BSc to Post Doc. Their previous experience working from home differs -which is acknowledged during data analysis, together with information on their domestic and home workspace set up. Many of the participants were employees of the same workplace building that the studies in chapter 01 took place; but given the wider scope of this study, the recruitment was not limited to the employees of this office building alone.

Table 3: Participants

Participant Number	Age	Gender	Level of Education	Occupation	Previously working from home	Health Conditions	Domestic Set Up
P01	55	m	MSc	Researcher	8 years remote work IT consultant	N/A	Lives alone in a flat, has a separate room for work office
P02	31	f	PhD	Researcher	2 years occasionally	N/A	Lives with partner at a house, shared home office
P03	27	f	MSc	Interaction Designer	None	N/A	Lives with partner at a flat, shared home office
P04	32	f	MSc	Manager	None	PTSD	Lives with partner at a house, separate home office
P05	36	f	MSc	Software Engineer	3 years remote engineer	Endometriosis	Lives alone in a house, no home office
P06	22	f	BSc	Psychology / Social Work	None	N/A	Shares room with partner at a flat share, no home office
P07	40	f	PhD	Researcher	1-2 years occasionally	N/A	Lives at a flat with family, works at bedroom
P08	30	f	PhD	Architect	None	Pregnancy	Lives at a house with family, works at living room
P09	28	f	MSc	Researcher	None	N/A	Lives at a house with family, works at bedroom
P10	40	m	PhD	Medical Economist	2-3 years occasionally	N/A	Lives at a flat alone, works at living room
P11	35	m	MSc	Researcher	None	N/A	Lives at a house with family, home office is at garden house
P12	40	m	MSc	Researcher	2 years occasionally	N/A	Lives at a house with family, home office is shared with partner
P13	37	m	MSc	Researcher	None	ADHD	Lives at a flat with partner, home office in separate room

5.2.3. Data Collection: Data and Technologies for self-tracking

The study focuses on quantification in rather than of the buildings of work; bringing the concept of self-tracking in the workplace and employing wearable bands to generate data sets. Participants interact with their data through a wearable display (see next section), and can choose not to wear this band after working hours (to protect broader aspects of their personal lives). The framing of this study under the concept of the 'quantified self' (self-tracking) in the buildings for work allowed flexibility in generating datasets using bespoke devices without having to rely on a fixed building sensory system and the familiarity of the participants with it (as per previous Chapter). Wearable sensors were preferred over other types of desk-placed sensors (for instance, air quality sensors) as they were easier to carry around in the house; again, with the view of being as little interventionist to the natural context as possible.

The study was conducted using commodity wearable bands Mi band 2 and a purpose-built static web app (hosted in GitHub pages, Firebase database). Both technologies were used to collect multivariate time series data - through sensors in wearables, and custom sliders in the app – and images and text entries by prompting participants to briefly respond to some questions about their experiences and wellbeing while working.

Wearable band Mi 2

Commodity bands Mi2 (Figure 36 (A)) were mainly selected due to their usability advantage and their widespread acceptability and adoption as activity sensing devices. They are easy to use without prior technical knowledge or extensive support. They provide feedback to their users through a display, with vibration and sound notifications. They are already widely adopted in the workplace which endorses the reasoning for selection. The reasoning behind the use of wearable bands for data collection was to explore the potential of wearables as sensory devices and feedback mechanisms at the workplace. Collected data included step count, distance, heart rate; providing a grounding for understanding daily activity while working in the domestic set up; and an indirect assessment of wellbeing (in correlation with self-reported data). The accuracy of activity data -i.e. distance and step counting - is high as the devices have good accelerometer & gyroscope. Heart rate data were sporadic after user's initiated the measurement. The downsides of commodity bands to provide continuous accurate measurements and pure raw data for analysis were less important for the purpose of this study; whereas their potential to provide feedback as a wearable display were interesting and relevant. Future work will consider higher precision sensors to record activity, heart rate and ambient environment data.

Purpose-built diary Web App

The static web app[113] offered an easy-to-use interface for documenting aspects of wellbeing and to characterize the individual workplaces using sliders, text input fields (diary entries) and image uploads. Designed to work as a diary and a survey, it addressed both qualitative and

[113] The app was developed in HTML5/CSS3/JS, hosted in Github Pages & using Firebase real-time database to timestamp and store the data.

quantitative aspects of the participants' daily experiences and wellbeing. The custom sliders[114] (Figure 36 (B)) were developed for the purpose of self-evaluating aspects of wellbeing and the surrounding environment. All sliders ranged, presenting with a default setting of 50. The sliders that used to evaluate the surrounding environment addressed temperature (cold - hot), light (dark-light), noise (noisy-quiet), air quality (poor-fresh). The sliders used to evaluate wellbeing dimensions were based on the Circumplex Model of Affect [115] (Russell 1980, Schimmack and Grob 2000) [29,194,405] (Figure 36 (C)). These dimensions are valence (negative - positive), arousal (tired - energetic) and stance (relaxed - tensed). Additional to these, stress (calm-anxious) motivation (motivated-non motivated) and productivity (productive-non-productive) were included as sliders. The use of colloquial language to address the measures was used to facilitate better communication with the participants; similarly, the use of the word 'mood' to reflect on emotional wellbeing. Based on interviews, it did not impact their understanding of the questions addressed. The environment and affect measurement sliders were designed with a reference to validated tools such as the Affective slider [29] and were pre-tested with a group of 5 users prior to the study.

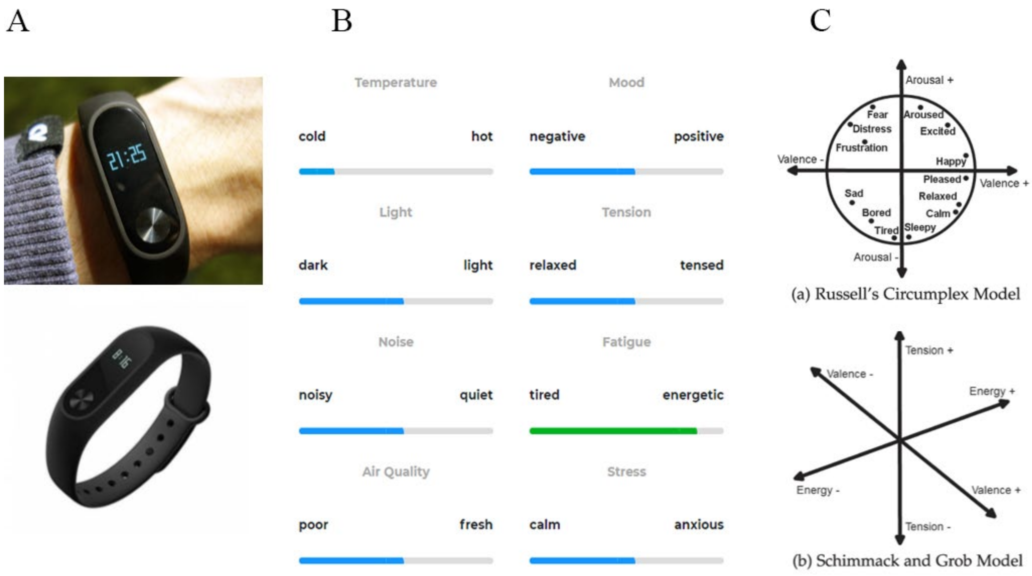


Figure 3635: A The wearable used, B the sliders developed, C Circumplex Model of Affect

5.2.4 Data Analysis

Wearable data (activity type, distance, step count, heart rate) were exported from the Mi bands by the participants and emailed to the researchers. Web data (pictures, text, slider entries)

[114] Sliders have a scale of 0 to 100 starting from a neutral position (50%). Any movement either directions was recorded a shift from the neutral position with a percentage and a timestamp. The sliders were changing color from green to light blue without indicating any connotation between color and positive / negative evaluation.

[115] The Circumplex model of Affect (Russell 1980, Schimmack and Grob 2000) served as a basis for developing the sliders around the felt self. The model addresses the dimensions of valence (pleasant-unpleasant or positive - negative), arousal (activation-deactivation or energetic – non energetic) and stance (low tensions – high tension). These dimensions are used to map the spectrum of participants mood.

were exported from the database and organized by the researchers. Interviews were recorded and transcribed using Zoom. Collected datasets were categorized in qualitative data – e.g. pictures, diary entries and interview transcripts – and quantitative data – e.g. slider entries, wearable data – and were further processed and analyzed independently.

5.3.4.1. Qualitative Data Analysis

Diary entries and interview transcripts were themed following a thematic analysis approach [60]. I coded these transcripts extracting statements on self-reported wellbeing -e.g. I feel low today, I feel positive today, I did not sleep well, I feel constantly worried etc.- statements on the experiences and engagement with the physical workspace - e.g. there is too much noise, I changed room I work today, I cleared the notes on my tables, I have a water bottle on my desk etc. – activities and routines – e.g. I did yoga in the morning, I do small breaks to cook etc.- and finally, on technologies and feedback – e.g. I like the vibration from the band, the web diary made me consider talking to my manager about my anxiety. Pictures (with or without annotations) were qualitatively analyzed and used to support the statements on the experience and engagement with the physical workspace (spatial and ambient aspects).

Qualitative Data (text and images) include:

- Interview transcripts of 13 participants – 30' mins each
- Daily diary entries of 13 participants for 4 weeks.
- Pictures of spaces (with or without annotations) – number of images per participant varies.

5.3.4.2. Quantitative Data Analysis

Multivariant time-series data included repeated measurements of wearable sensory data (distance, step count, heart rate) and self-reported wellbeing and perceived environment data (slider entries, percentage values). Data sets were combined into a dataset and cleaned by the researchers, addressing default and missing values.

Default values were sometimes reported when the users did not manipulate a slider; either because they felt covered by the default value (50%), or because they did not have an opinion on the matter at that moment. Additionally, heart rate data were often sparse. I chose to approach these entries as missing data (N/A). Missing entries were addressed through linear interpolation using the ImputeTS library and the kNN (k-nearest neighbor) in the sum of participants data. I consider that N/A values had limited impact on the findings.

Datasets were then processed in R studio following relevant methods (see Rmcorr, Auto-sklearn) to use the most of their statistical power. The analysis followed two main pathways, 1) exploring multivariant correlations and 2) testing the predictive power of the data:

- Correlation analysis of multivariant time-series data: self-reported (emotional) wellbeing data – e.g. valence, arousal, stance dimensions, stress and motivation-perceived aspects of the environment – e.g. light, noise, temperature, air quality entries – and wearable data (steps, heart rate). The aim of this analysis was to unveil multivariant correlation patterns in the sum of participants data. Correlation methods were first applied the sum of data using Corrplot to establish correlation coefficients; then in pairs of variables within and between participants using Rmcorr[116] [21] to establish the statistical significance of results.

- Prediction of dimensions of wellbeing based on self-reported ambient environment and wearable data. This analysis explores the potential of predicting wellbeing solely from variables that can be captured using passive sensing, to draft the design implications and the feasibility of automated predictions for future work. ML models applied were decision trees and random forests to establish the predictive power of various variables; and multiple automated ensemble learners using Auto-sklearn (python) [21] to explore the potentials of predicting valence based on environmental data only.

5.3. Findings

5.3.1. Qualitative Data Findings

The qualitative analysis concluded to three main themes which are unpacked further below: making a space for work at home; the challenges of embodied wellbeing in the lived workspace; and the value of feedback for the remote home worker.

5.3.1.1. Making a Space to Work at Home

Bringing the 'office' home requires specific space use modifications – such as finding a space or a corner, having a desk (or a table), a chair, one or more screens etc. – to take place. Participants tried to satisfy these criteria following different approaches. As a result, domestic lived workspaces look necessarily messy and chaotic. Analyzing participants' pictures, I identified some underlying principles that they follow to structure their home offices. These principles could be described as a) supporting basic ergonomics– e.g. surface leveling, positioning and orientation of displays b) forming visual cues and peripheral constraints – e.g. visual barriers to limit external distractions and guide focus, c) supporting comfort – e.g. across multiple dimensions such as kinesthetic, visual, thermal, auditory, etc., and d) providing positive engagement – e.g. objects for relief and self-entertainment. Due to different needs and the lack of space, diverse approaches to structuring spaces through the above principles are discussed below, drawing on the pictures and diary quotes participants provided.

- *Basic Ergonomics in Limited Space: Leveling and Displays*

During interviews, 7/13 participants mentioned that they prefer having a fixed home-office set up and have the option to alternate between working at home or at the office. 5/13 participants

[116] Jonathan Z.B, Laura R.M. 2017. Repeated Measures Correlation. Frontiers in Psychology. Doi: https://doi.org/10.3389/fpsyg.2017.00456

stated that they need their home office to have a good chair and a table/ desk surface that can fit a monitor, their lap-tops and notebooks as minimum requirements. Congestion of objects due to lack of space was a common theme as seen in their pictures (see Figure 37 (A), (B) – P07), resulting in poor ergonomic arrangement besides their best efforts.
Most of the connected workers spend their days in front of a screen and many mentioned their need for more and bigger display areas. A few brought extra monitors at home (6/13).

> *"We had one separate screen at the office; having more screen space helped me a lot. I sort of wanted to replicate that a bit when working from home. I set things up with two monitors plus my laptop and I find that I find like work better that way." P01*

A few (4/13) mentioned that they used a spot with stable screens and they move their lap-top around the house if they need to change spot. Some (6/13) used solutions such as lap top risers or trays to increase their work surface, bring objects in the right reach zone, or position displays in the right visual height. P03 uses a lap top riser utilizing surface space when working with her partner (right) or in the living room (left), while bringing the display to the right eye-level (see Figure 37 (C), (D)).

Figure 36: Desk and screen positioning at home

- *Visual Cues and Peripheral Constraints*

A few participants mentioned (4/13) using their desks or surrounding wall surfaces as display extensions, sticking notes as reminders. Three (3) participants mentioned piling post-it on their desk relevant to online meetings or the tasks they are working on that week and changing them when the task changes.

> *"I clean all my notes on the desk when I start on a new project" P07.*

Observing the pictures, a few (4/13) prefer having a neutral periphery with their only focus point on their screens, whereas others populate their desktop periphery manually extending their display spaces (see Figure 38 (A), (B) - P12 below).

Apart from expanding their displays in the periphery, there is also a need to constrain it. A few used covers or furniture as elements to block or filter visual distractions. In Figure 38 (C), P13 uses a shelving unit that blocks view in the rest of the room, while P01 (Figure 38 (D)) uses blinds to manage light and the view.

Figure 37: Use of barriers and surrounding surfaces

- *Comfort and Ambient Aspects*

Comfort has many dimensions, such as visual, auditory, thermal etc. The discussion below highlights participants' actions to maximize their comfort, addressing aspects of natural light, visual contact with the outside, ambient color, and noise.

Ambient natural light came in many quotes as essential. Observing the participant's work desks, most of them face a wall with a window -the source of natural light- located either on the right or left side; with only 3 of them facing it. Most of them prefer natural light coming on the right or left side of their desks, avoiding getting blinded. A few (2/13) repositioned, rotated, or levelled their displays to balance blurring and the direction of light coming in the room. Some (4/13) mentioned that they avoid facing their windows while their work - direct visual contact with the outside - to avoid visual distractions such as movements of cars or people. The few that choose to face their windows mentioned enjoying ambient movement and visual contact with nature while they work (2/13).

> *"I like the movement from the construction site outside the window, it feels like something is going on. ... I used to work on the train, I liked the movement outside the windows." P01*

In Figure 39 (A), (B) below changing their screen positioning depending on the ambient light in the room (P10) while maximizing visual contact with nature – using the window as a calming display. It was also common in participant diaries to refer to the weather and the colour of the sky, in relation with their wellbeing (mood) (12/13): *"I feel a bit low today, and it is so grey and rainy." P02* A few mentioned using white sound (2/13) and nature soundscapes (1/13) to neutralize or cover noise from outside. Many mentioned that they enjoy listening to music without headphones in their home office (4/13).

A B

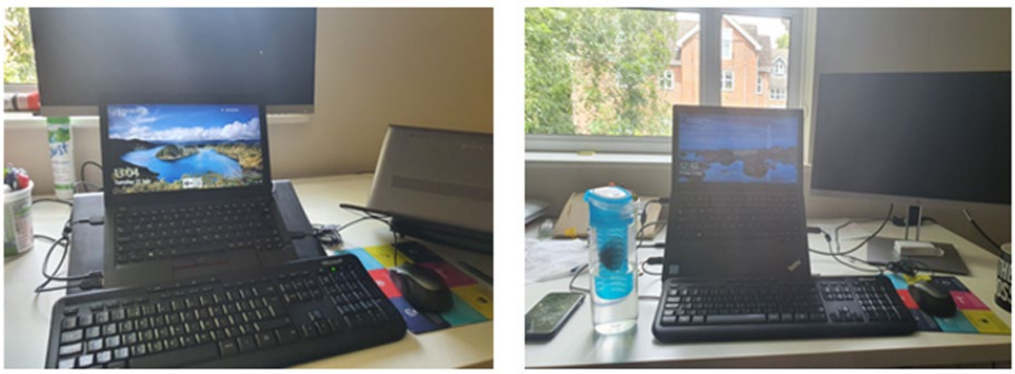


Figure 38: Contact with Nature

Some mentioned using day light lamps to balance insufficient natural light in the room or extend their working hours (2/13), positioning day-light lamps on their right and left sides of their work desks. Diary quotes and images suggest that 7/13 generally prefer neutral-coloured spaces to work, with a few (4/13) prefer more colourful spaces, adding posters in their periphery.

> *"I need a neutral space to work, I try to neutralize the environment around me from sounds or colors, and make sure that it is not something I update every day." P07*

Some participants (2/13) said that they found different spaces in their home to offer different dynamics - *'more creative tasks can happen in more colorful and messy spaces' P13*, whereas *'thinking requires neutral spaces' P07* (Figure 40 (A), (B)). A few said (3/13) they choose their spots depending on what they are working on, how they feel or depending on the weather and light in the house.

> *I think if I need to be bit creative it's better for me to sit in the living room where there are more colors … more colors can also work distracting. If I need to concentrate, I find concentrating there harder." P13*

- *Providing Positive Engagement*

Finally, plants, decorative elements, de-stress balls, and musical instruments were very commonly placed in the participants periphery to enhance positive engagement with their workplace (Figure 40 (C), (D**))**.

Figure 39: Colors and positive engagement

5.3.1.2. The challenges for Wellbeing in the lived Domestic Workspace

- *Changing spots: conflicting needs for Variation, Structure, and Flexibility*

Several participants (4/13) mentioned changing workspaces as an inherent part of their workday when working outside home, visiting different spaces in a building, or working in different buildings. Many mentioned missing the variation of spatial experiences when working from home, and that it is something hard to re-create.

> *"I used to work from the library or from the office and then go and teach in the medical sciences faculty. Then, suddenly, it is just one room." P09*

Still, the domestic workspace often requires a level of flexibility to balance conflicting needs. Some said (6/13) that they need to have a fixed workspace in their houses, while others (5/13) claimed to be more flexible and work in their living areas, kitchen tables or often change locations in the house. 3 more participants mentioned that besides their preferred fixed spots, they sometimes alternate locations in the house to satisfy family life.

> *"I really do not mind working on the sofa or the kitchen bench; Wi-Fi is actually better here." P05*

> *"I work in whichever room is available. Currently I have a desk in our sewing room, next week I will work at the dining table." P04*

The more 'flexible' participants (5/13) mentioned that they can 'blend' their workplace with other domestic spaces without having critical focus issues or task-prioritization conflicts. A few (2/13) mentioned that changing work spots help them regain focus.

> *"I realized I like changing space for working, it helps with focus attention." P02*

On the other hand, the participants (6/13) that seemed to be more sensitive on their set up mentioned that they prefer to have a separate workspace from the living areas, keeping a clear division between 'work' and 'domestic' life. A few of them mentioned challenges to do so, such as the lack of space and conflicting priorities between domestic and work life, or different aspects of remote work in the same space.

> *"We share the office room and desk with my partner as we tried to separate our work from the living space. We do not have much space as you can see in the pictures. If one has an online meeting at the office space, the other moves in the living room so we do not disturb each other." P03*

- *The lack of Rhythm and Pacing*

Many mentioned the lack of 'rhythm' during their day, which often occurred from informal chats with colleagues. With no informal social interactions at place, it seems that both the engagement with work and the quality of breaks was getting poorer (3/13).

> *'The working day needs a rhythm. working from home is constantly relaxing or static. There is no variation or change." P11*

> *"Now actually need to sort of entertain yourself to actually have breaks. you're sort of beating yourself up about not maybe doing enough work and then on the other hand, you're not taking off like quality, quality breaks, either" P03*

A few mentioned that they feel that the lack of pace in their workday results to them feeling too relaxed, unproductive, and extend their working hours (2/13). Similarly, many participants find hard to zone in or out of work in their homes, unless they leave their rooms. A few find alternating between domestic and work life easier (3/13).

> *"Being too flexible results being unstructured or not having a clear routine ... my schedule becomes too irregular, and I work until very late at night." P11*
>
> *"I do not have an issue with zoning out of work in the living room, I just turn my lap top off." P05*

- *The lack of Movement*

Physical activity is important for health in daily work life. 10/13 of the participants recognized the importance of daily movement as part of their workday. As connected workers do most of the work in front of a screen, many mentioned (9/13) that they walk much less at home, as there is no need to go somewhere and the distances in the house are much smaller.

> *"At the office, I would walk to meetings, rather than do three hours of video meetings. Walking would be part of my routine, because normally I would walk across the campus to another meeting room. I don't really walk much when I work at my house. I go up maybe for a cup of tea, you know, that sort of thing." P04*
>
> *"When I go to the office, I have to run around between the warehouse and my desk. That is why I walk more. Whereas when I am at home, I am just with myself and the computer." P08*

A few mentioned that they 'forget' to move away from their chairs for long time as they work uninterrupted. A few reported increased fatigue (3/13) and eye conditions from long screen staring (1/13). Many reported lower backpain (6/13) from sitting too long at their work desks. Back pain problems also rise due to the use of non-ergonomic furniture -such as kitchen chairs- as office furniture, resulting sitting long in the wrong postures. A few (2/13) also referred to irregular breathing – e.g. holding their breath due to stress or concentration – relating it with fatigue their experiencing.

> *"I have back and neck pain again, I have been sitting too long to concentrate on research ... I feel I am not productive enough, and no-one interrupts me. You tend to forget about the time, you forget to do breaks." P11*
>
> *"Because I am concentrating on a project, sometimes I think I stopped breathing properly. I believe that is kind of thing, is making me fatigue because of the lack of oxygen." P11*

Some use different furniture to work (3/13) and avoid sitting too long in the same posture; or take short breaks to lay back.

> *"I get a lot of lower back pain because of sitting too long. One good thing of being at home is that I can take short breaks to lay back on the sofa and relax." P08*

Finally, a few observed how physical activity helps them think and changes their experience of the surroundings while working. They mentioned that physical activity helps them deal with noise distractions; feeling better because of 'fresh air', and that lack of physical activity changes their perception of temperature.

> *"Walking works for me, it gives me a lot of time to think. When I'm coming back, I am more efficient. It is not that noise becomes less prominent, but you are more resilient to accept the distractions than before." P07*

> *"I start feeling cold if I sit too long; I know it is not colder than usual, but it feels like it is." P13*

Most participants refer to restoring from bad mood and fatigue is through outdoor & indoor physical activity, either pre-planned or spontaneous. Many mentioned taking short active breaks during workday- stand up to stretch, yoga, walk or jump inside the house (5/13), plan a physical activity to start or end the workday (4/13) as 'waking up ritual' and 'a mental preparation for work', and practicing breathing techniques to relax. (1/13)

> *"I just jumped around the house to shake off the tension of writing the paper. ... During lunch I did some yoga, which was nice to recharge for the rest of the day." P03*

> *"As every day, I started the day with yoga & I practiced Buddhism (morning/evening)." P02*

> *"What really helps to control my stress is focusing on my breath, doing a breathing meditation – I practice box breathing for a few minutes while I work." P08*

- *Distractions in Isolation*

Noise from construction sites or the street was mentioned most in the diaries and interviews as one of the main causes causing cognitive overload, irritation and fatigue while working (4/13). Escaping from noise while working at home is a challenge; some mentioned shifting their working -hours resulting in working late or closing windows – resulting in low air quality and high temperature.

> *"For example, I close the windows because there's a building site next to our house and they can be really noisy throughout the day. But it's very irregular." P13*

Other mentioned that distractions *"are often more internal than external. It is a lot about managing own's thoughts and emotions" P13*, referring to persistent negative thoughts and emotions (4/13). A few mentioned getting 'stuck' in a negative mindset regarding their work or themselves without being able to 'get out' (4/13). Some addressed (2/13) that it is hard to stick to what is good for you; being unable to manage yourself in a way that is good for you or do anything to improve the way you feel.

"If you don't feel so well, I think you don't have the discipline to do the things that are good for you. Because they often need some engagement, you need to make it choice to stop and start again. And to be able to do that, you need some mental energy." P13

"If something goes wrong, I have no one to bounce off at all. If I get into a negative like or stress kind of headspace, I just stay in it." P04

Finally, some mentioned being overloaded and distracted by notifications from diverse collaboration tools and social media for work (3/13).

"We have three different platforms that we communicate with my colleagues. One day last week all three of them were buzzing non-stop. It was email, then teams, and discord which we use for community. I keep this window open and try to answer all of them, but it was a bit crazy to deal with all of these. If you are in our office, you just talk to the person." P08

5.4.1.3. The value of Feedback for the Remote Worker

Many participants mentioned that since working alone, they relied even more on following a schedule and setting notifications to make sure they keep up with it (8/13). A few of them used tools to help them structure their workday and support their wellbeing (3/13); alarms to manage their schedule (2/13), reminders for activity breaks (2/13), while some went further checking their breathing patterns (2/13) or controlling calories (2/13):

"I use pomodoro to set up working intervals and make sure I take regular breaks." P03

"I bought a band to check the oxygen saturation levels in my blood; I believe that I get fatigued because of the lack of oxygen." P11

Below the participants opinions around the use of the provided wearable devices and the mood-measuring tools in the context of domestic workplace.

- *Feedback to Move*

Many participants (10/13) found the band pleasant to wear and non- intrusive. A few said that their daily exercise was somehow fixed and did not need any reminders for this (5/13) or that the band was not accurate in terms of measuring other types of activity such as yoga or cycling (4/13).

"I do a walk or a cycle in the morning anyway; it is irrelevant with the band ... I am not a smart person motivated by targets anyway." P01

"I do yoga every morning, but I feel it does not measure that…it only measures steps." P02

Still, many mentioned that it made them more aware of the fact that they walk less during their workday through the display of steps (6/13), and that the band worked very well for this purpose. Some stated that it was more effective than mobile apps, as you wear it all the time. Some mentioned that they use it to set up a daily step goal (3/13) and tried to keep up with it.

> *"I didn't set any particular targets, but when you check the steps and see how little you have walked…well it motivates you to move." P06*

> *"I have a mobile app for step counting and calories, but it is not as effective as the band – it is always on your hand." P10*

Others used the alarm to set up regular breaks from work (3/13). They mentioned that the vibration was pleasant as a movement reminder, whereas noise or voice interruptions where not that positive.

> *"I loved waking up with the vibration, it was a nice experience." P02*

> *"…also the band vibrates and reminds me to take often breaks." P04*

- *Feedback for self- reflection*

Many participants (5/13) mentioned that it was hard to describe and evaluate how they actually feel during their workday. As they get absorbed in their work in remote, they mentioned not paying much attention to themselves (e.g. their body-posture) their surroundings (e.g. working under poor lighting), or their wellbeing while working (e.g. getting caught in a bad mood). The ways they described their emotional wellbeing in their diaries can have many interpretations; they often made associations with to explain how they feel to themselves – i.e. I feel low because I had bad sleep, the weather is bad, I have too much work, or there is too much noise and that irritates me etc – but it is unclear if these aspects are causing the problem or they come to their attention because they feel low. Using the sliders was meaningful in that case to provide a mental anchor and a measure that they can assign to how they feel. Many mentioned that the diary and the sliders initiated their emotional self-reflection by setting a scale and aspects to consider; others claimed that it helped them in trying to understand potential causes of it. A few (3/13) mentioned that they started checking their environment & work set up more often to make sure they have adequate light etc.

> *"I actually start observing how the light and air quality is while I am working at how it might affect me." P13*

A few noted that they enjoyed keepingt diaries trying to see patterns in their emotions and thinking (4/13) whereas others preferred manipulating the sliders over writing extensive text (4/13).

> *"I found the diary meaningful to try to understand my thought/emotions patterns better and find ways to manage it." P07*

A few mentioned that the self-reflection exercise was meaningful for self-management (3/13); and that it pushed them to take action on changing what caused them discomfort (2/13).

> *"Participating was an interesting self-reflection exercise for me. The study pushed me to realize I was not alright and talk to my manager about the fact that I am constantly anxious." P06*

Others mentioned that being made aware of their emotions and learning to accept them was an interesting part of the study (5/13). The majority found the diary study unobtrusive, but a bit tiring and repetitive, suggesting that more variation in the questions based on context and previous entries would be meaningful. Some pointed to further considerations and improvements, such as:

> *"Allowing better self-management through visualizing mood and activity circles." P11*
>
> *"I would like to be able to see a visualization of my mood fluctuations." P02*
>
> *"I would like to have an archive of my previous entries to understand my mood and thought patterns." P07*
>
> *"I would like to have more personalized questions based on previous answers I gave, to help me gain deeper insights to what actions can help me." P12*

- *From awareness to changing behavior: attitudes on feedback*

In summary, there were diverse reported attitudes regarding the impact of the wearable and diary feedback. A few (4/13) responded that feedback was a merely self - confirmation:

> *"I was feeling tired, the survey made it clear to me that I need a holiday" P04*
>
> *"I know I do not walk much, the band just confirmed it." P04*

The majority mentioned that the web diary increased their 'self-awareness' about their own wellbeing fluctuations and thought patterns (6/13) and helped them cope with the situation (2/13) or nudged them to act (2/13). Participants mentioned that they used the bands to set reminders and goals to move more often; and that they were useful in pushing them to have regular breaks. Still, it is unclear if the band helped participants to form healthier habits in the long run and without 'on the spot' reminders. 7/13 stated they will keep using the band after the study; but no data has been collected on how they use it and if their behavior shifted.

5.3.2. Quantitative Data Findings

5.3.2.1. Aspects of the environment and embodied wellbeing: a multivariant correlation analysis.

This part of the analysis focuses on framing correlations between repeated measurements of self-reported wellbeing and ambient environment, and activity and heart rate data. Multivariant timeseries data included wearable activity data (distance, step count, heart rate), and self-reported data on wellbeing (valence, arousal, stance, stress) and perceived environment (light, air quality, temperature, noise) recording values from 1-100 from the custom sliders.

Figure 41 illustrates the correlation coefficients for all wellbeing and environment correlation combinations. The analysis shows a moderate positive correlation (R=.54) between perceived air quality (poor-fresh air) and valence (negative-positive mood). The analysis also shows a mild negative correlation between air quality and stance (R=-.36)- i.e. decrease of air-quality and increase of tension- and stress (R=-.22) – i.e. decrease of air-quality and increase of stress. There is a very mild positive correlation (R=.23) between arousal and air quality – i.e. feeling energetic when perceived air quality increases. The analysis also showed minor positive correlations between noise and valence (R=.25)- i.e. positive wellbeing in quiet workspaces - and light and valence (R=.19) – i.e. positive wellbeing in more well-lit spaces. While these correlations do not represent a particularly strong association, noise and light were frequently mentioned in the qualitative data.

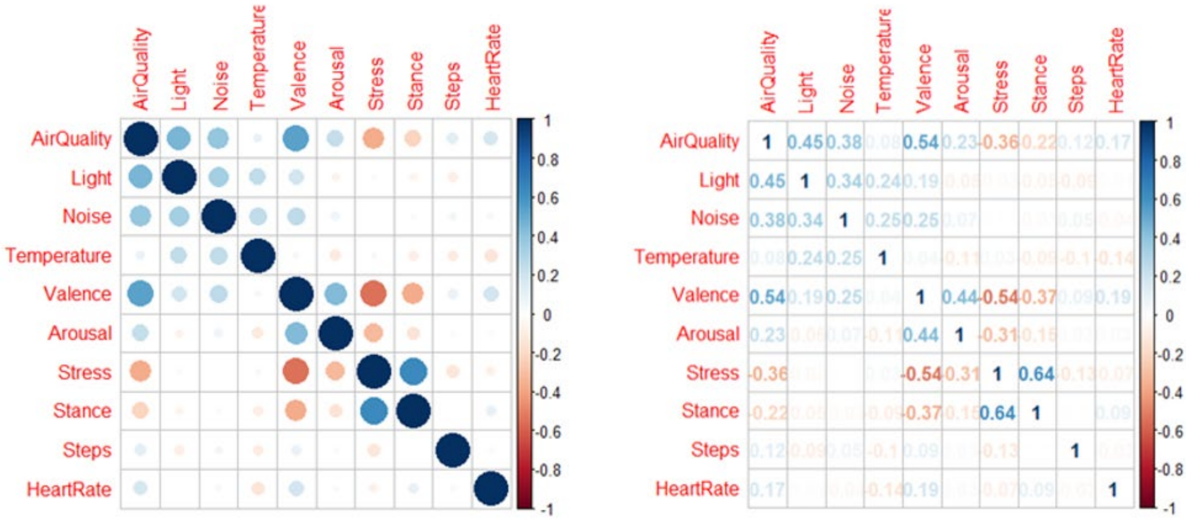
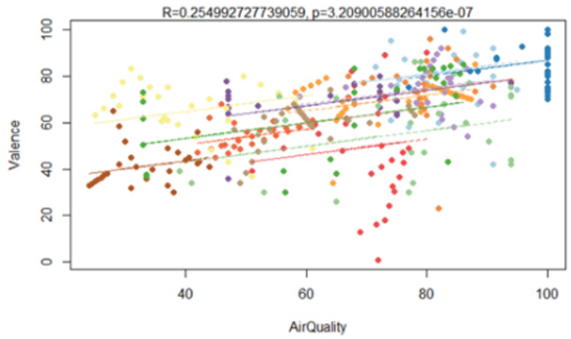
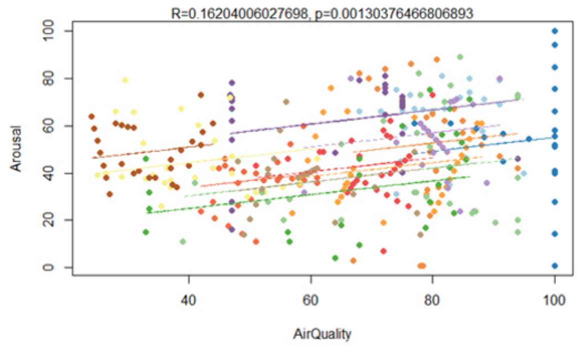


Figure 40: Correlation coefficients for all wellbeing and environment aspects correlation combinations

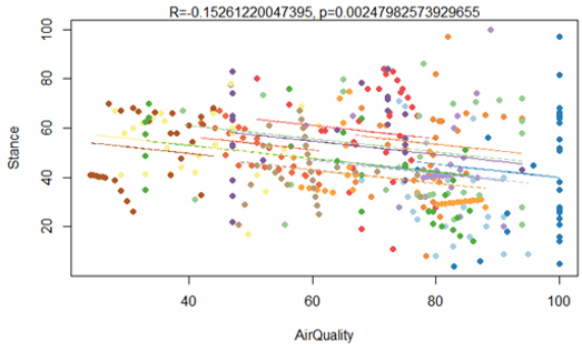
Similar results occur using Rmcorr - repeated measures correlation - highlighting the impact of air-quality on emotional wellbeing (mood), also establishing the statistical significance of these findings. Below (see Figure 42) the correlation graphs of the most significant R and p-values for pairs of variables in the sum of participants; each participant is represented in a different color.



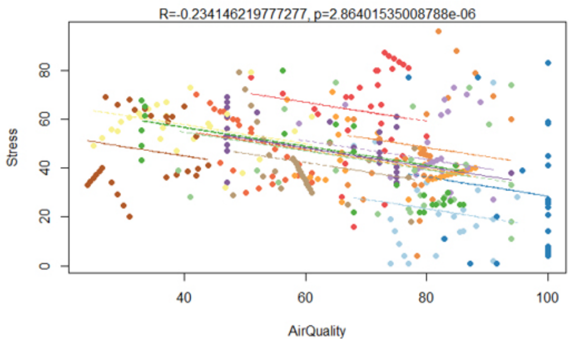
Valence- Air-quality: Moderate positive correlation not statistically significant (R=0.25, p=3.2)



Arousal - Air-quality: Mild positive correlation, statistically significant (R=0.16, p=0.001)



Stance- Air-quality: Mild negative correlation, statistically significant (R=-0.15, p=0.002)



Stress- Air-quality: Mild negative correlation, not statistically significant (R=-0.15, p=2.86)

Figure 41: Air quality and dimensions of wellbeing (mood) correlations

We also examined the relationships between self-reported wellbeing dimensions to understand how these relate with one another and validate data coherency. Valence and arousal have a mild positive correlation with no statistical significance level (R=.37, p=2.44) meaning that feeling energetic loosely correlates with feeling positive; similarly feeling in low mood loosely correlates with higher tension.

The outcomes indicate a relationship between air quality and valence motivating further study, as passive sensing devices for air quality are readily available; yet the persistence of the association with passively collected sensing data for the context discussed in this work remains to be validated with a greater sample of participants and sensory measurements.

5.3.2.2. Predictive potential for emotional wellbeing based on passive environmental sensing.

This section further explores the possibility of predicting self-reported affective states from environmental measures. I modelled the prediction of each of the parameters: valence, arousal and stance; based on the self-reported environmental data (light, temperature, noise, air quality) and the passively collected activity data (steps, heart rate). Random forest training and multiple regression modelling approaches suggest that environmental data have a greater predictive power on valence than the rest of self-reported wellbeing data (stance or arousal). I continued with exploring predictive potentials of valence using decision tree modelling to obtain an explainable model based on solely environmental data. This selection was based on the results of multiple regression modelling and a categorical separation of environmental and activity data. The decision tree based produces the diagram below (see Figure 43), highlighting the importance of air quality (see top node and layer 2). The confidence level is above 90% for each node. Addressing the extremes, Node 10 suggests that if Air Quality obtains a value above 77.75 (i.e. fresh air) and Temperature a value below 47,25 (i.e. cool temperature) Valence would have a value of 85 – i.e. very positive valence when working in fresh air and cool temperature. Node 4 indicates a low valence (below 40) occurs when noise is high (below 41) and air quality is low (below 56). This approach provides the basis of setting rules and constraints in design of future user-driven systems, given that inputs (Air Quality, Light, Noise and Temperature) will be actual sensory measurements.

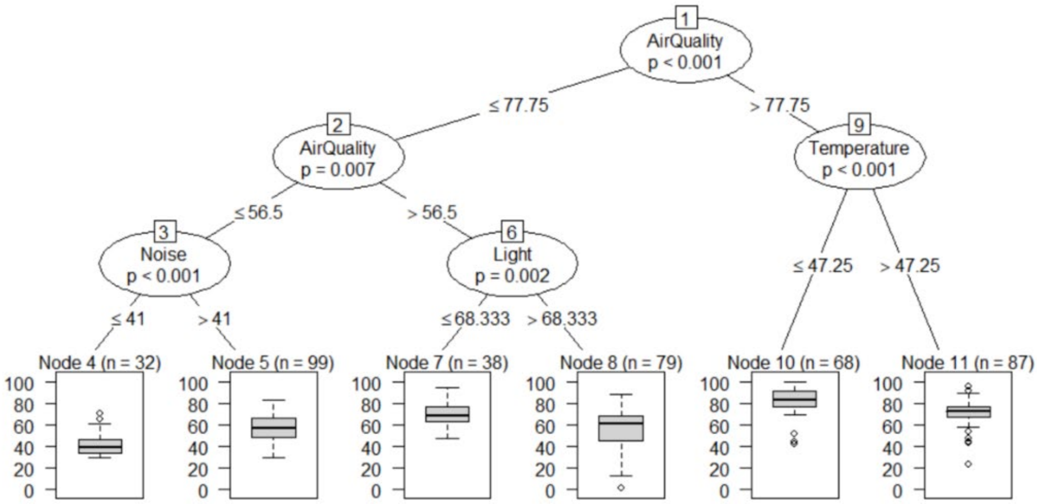


Figure 42: The decision tree of environmental and activity data

Finally, automated predictive ensemble composition using the machine learning (ML) package Auto-sklearn [21] was used to explore best candidate regression performance to predict valence ratings based on environmental factors. The model indicates a strong correlation (R2: 0.7) when employing a 240s runtime limitation with a threshold of 30s per individual model training with a feature set of: air quality, light, noise, temperature, steps, distance, and heart rate. Prediction based on the activity sensing data alone resulted only in a weak association (R2: 0.3). For practical purposes, using the same framework and runtime settings, I also explored the medium or high values for self-reported Valence, using automated exploration (auto-ML) of a structured hypothesis space of 110 hyperparameters (based on 15 ML models). The resulting ensemble indicated an overall best possible accuracy with the given data set of 80% (average precision 0.82, recall 0.63) after pruning to 3 features only (air quality, light and noise). Automated ML ensemble generation indicates that predicting emotional wellbeing from passive data may likely be possible, showing 80% accuracy in predicting low/medium/high valence classes and an R2 of 0.3 for prediction via regression.

Acknowledging that this remains a group-level exploration and early indicative findings for now, it indicates a good reason to aim for further validation using passively collected ambient data and a greater sample of participants and repeated measurements. If that is successful, individualized models should also be explored as they can reasonably be employed for workplace usage and would likely lead to much more reliable predictions - as they would respect individual characteristics and contextual information from the workplace.

5.4. Discussion

5.4.1. Reflecting on field observations

The analysis of collected data has provided some interesting and significant findings in relation to the research questions **(RQ1, RQ2)**. The qualitative results addressed the physical and wellbeing challenges while working from home, such as the lack of movement and the difficulties separating and transitioning between work and domestic life **(RQ1, RQ2)**. The quantitative data highlighted significant correlation between perceived air quality and emotional wellbeing (mood) and highlighted the potentials of predicting emotional wellbeing in remote home offices based on passive data capture **(RQ2)**.

The challenges of managing office ergonomics in limited, often shared workspaces, and with diverse space-use were highlighted in diary quotes and pictures **(RQ1)**. Participants illustrated a diversity in their needs for spatial structure, flexibility and spatial variation while working from home. Participants had different needs in terms of structure to engage with work and expressed different levels of spatial autonomy with regards to their work tasks (**RQ1)**. Some participants took steps to deal with the problems of limited space adapting levelling, positionality and orientation of surfaces – e.g. creating barriers or using stands. Changing spaces and manipulation of spatial affordances was mentioned with regards to task switching and zoning out of work (**RQ1)**. These actions point towards designing for work surfaces with a greater adaptability to match with the lack of work areas and the changeable space-use needs, while ensuring ergonomics and comfort **(RQ1, RQ2)**. The work of Petersen and Grønbæk et al [137–139,294,295], as well as Takashima and Leithinger [199,363,364] is an example of such interventions; with a focus on informal collaborative work in office spaces whereby shape changing interactive desks initiate dynamic work areas [137,137]. Moving forward, bringing adaptive furniture examples to remote home workspaces [34,246,274,291] would address enabling calmer transitions between domestic and work life and assist with different aspects of remote connected work [106,176,181].

The need for multiple display areas and the intuitive expansion of display in the periphery -e.g. the piling and cleaning of notes – point towards extending work displays to the surrounding physical environment **(RQ1)**. Reflecting the work on projected or AR displays [162,163,196,393], tangible interaction can extend work tasks beyond the screen. Other aspects mentioned by participants were feeling disconnected with colleagues, missing spatial variation and rhythmicity of the office space, and getting overloaded from using many online collaboration tools that often fail to address their needs (**RQ2)**. Moving forward, research on extending the display could help reduce cognitive load from long screen exposure and notifications [206,258,351,369], while engaging and interacting naturally with the physical space. Past research on physical displays in slow HCI and calm computing [140,206] illustrates the potential of physical interfaces to enhance co-presence through slow calm interactions with physical and material affordances [84,121,121,140]; and often engaging with spatial and material attributes. Physical interfaces bare potentials to bring the rhythmicity and flow of the workday to remote settings such as home office, through temporal data materializations and physicalizations.

Regarding ambient aspects and wellbeing **(RQ2)**, noise was mentioned as a core issue as well as the lack of natural light. The participants intuitively positioned their work desks and displays to better use ambient natural light in the room, enhanced natural light in the rooms using day-lamps, and referred to windows as light and calming displays – e.g. providing a view of nature (**RQ2)**. Some mentioned that different ambient light and ambient colour impacts their wellbeing (mood) and productivity differently, relating colour to creative work tasks (**RQ1)**. Reflecting past literature, ambient light has been used as mood feedback[345], stress biofeedback [410], eco-feedback[91]; a strategy for social connectedness and physical wellbeing [114,285,287,315]. Moving forward, ambient light can be explored as a social and self-awareness strategy in remote workplace in interaction with ambient noise and voice data.

From a quantitative perspective, air quality showed strong correlations with affect – e.g. positive mood and perceived fresh air quality-, particularly valence (positive- negative mood) and secondarily with arousal (low-high energy) **(RQ2)**. This is a very interesting aspect that appears only indirectly in the diary entries (e.g. mentioning fatigue from poor air circulation), but it was prominent when directly asked in the slider entries. What it means is that poor air quality negatively impacts wellbeing, but it is not brought to attention unless directly addressed. This suggests that air quality is an aspect that requires 'surfacing' to be brought to the occupants' awareness **(RQ1)**; as they tend to ignore it until they are directly asked to evaluate it. Indeed, it can be common that home workers forget to open the windows or ventilate their rooms adequately; and, sometimes having a window open for ventilation can conflict with noise or pollution coming from the outside. The interpretation of the correlation of air quality to valence accounts broader considerations relevant with the data collection methods. As these measures are based on self-reported and not sensory data, there are multiple interpretations assigned to air quality. Poor air quality can mean low oxygen, poor air-circulation, high temperature, high humidity, and the combination of these aspects. Poor air quality in terms of the experience of remote workers could even relate to their breathing patterns **(RQ2) –** i.e. participants hold their breath due to stress or concentration, get fatigued and report bad air quality. It can also mean the opposite, that when home workers are stressed, they might attend to air quality more – e.g. open a window to get fresh air and restore. The negative correlation between stress or stance and air quality also points towards these associations.

Nevertheless, the correlation of air quality with valence – e.g. good air quality makes building occupants happier – is interesting **(RQ2)** and needs to be validated with greater samples and sensory readings in future work; also identifying which aspects of air quality- i.e. air flow, CO2 levels, humidity etc. - are the most impactful to this correlation. The importance of air quality for workplace wellbeing is also highlighted in the growing attention it has recently received in the HCI community, enhancing the importance of early findings. Relevant work [83,104,344,344,422,423] addresses eco-feedback - including mobile and wearable visualizations, and ambient light notifications- and collaborative and predictive approaches to regulate air quality in office spaces [422]. However, the many elements of air quality experience in the workspace remain unaddressed by current research. Positioned within a broader sustainability agenda, the findings highlight the necessity of 'surfacing' indoor and outdoor air quality data for wellbeing in the remote / hybrid workplace; developing ambient technologies that address embodied experiences and engage the building occupants in becoming more aware and responsible in managing their micro-climate. The quantitative analysis also indicates that there are potentials of predicting core dimensions of wellbeing based on environmental and activity data **(RQ2)**; which will be also further explored in future work.

Although highly customizable and occupant-controlled, it appears that a level of feedback-mediated autonomy (AI) of remote workspaces would be beneficial for the occupants' wellbeing **(RQ2)**. This is highlighted by many of their quotes where they express getting too focused in work resulting to limited attention to their surroundings and their bodies; and the inability to constantly consider and balance all aspects of their environments **(RQ2)**. Moreover, participants found wellbeing self-reporting useful, and suggested they would benefit from wellbeing (mood) awareness strategies **(RQ2)**. Many of them stated that they would like to be able to have a visualization of their inputs of previous days and be able to observe their behavior patterns over time. Some participants suggested the use of personalized and task - relevant feedback depending on archived data **(RQ2)**. Regarding the predictive potentials of emotional wellbeing (mood), the analysis indicated good reason to pursue verification using passively collected environmental information **(RQ2).** The internally coherent picture between affective data and activity indicates an adequate reliability for these exploratory findings. For many ambient working applications, it would be interesting to be able to predict affective states from passively collected data and use these as feedback towards the users, or as the basis to form rules and constraints in Human-AI interactive systems in the built environment, that help remote workers become aware of and regulate their emotional wellbeing **(RQ2)**, at an individual and collective level.

The lack of physical activity and physical movement was highly marked both in qualitative and quantitative findings **(RQ2)**. Many participants mentioned that they do not move much during their workday as they have no physical distractions such as interruptions from colleagues and they can do everything from their desktop screens – including meetings -, resulting in reported back pain and fatigue; worsened by non-ergonomic furniture and the lack of breaks **(RQ2)**. Wearable feedback helped in tackling some of these aspects **(RQ2).** Participants stated that they found the bands non-intrusive, making them move more often through display, vibration, and alarm notifications, while acknowledging their limitations in data accuracy. On-the-spot wearable notifications for physical activity were successful motivators during the study, but it is unknown if this resulted in further changes in routines of the participants after the end of it. Physical activity – such as stretching breaks, cycling breaks, and walking breaks [82] - is beneficial for physical and mental wellbeing, but this is not encouraged in remote work [81]. The question is how to introduce physical movement as a core element of remote work, taking advantage of the success of wearable -mediated feedback [35]. The suggestion is to extend activity feedback beyond notifications, to (potentially wearable mediated)[134] ambient and physical interactions for physical activity – for instance, in combination with adaptive furniture[66,335].

As an overall note, it is important to highlight that as this data was collected and analyzed during COVID-19 lockdowns, the above findings represent an exaggerated image of the issues at home office. With this is considered, the discussion below framing a general direction towards designing for domestic and hybrid offices based on the key findings.

5.4.2. Framing a design agenda for future ambient workspaces

Our exploratory study addressed the embodied experiences and physical aspects of the domestic workplace engagement. This study identified some of the key challenges for the wellbeing of remote workers – such as the lack of activity and the limited or conflicting space-use. There are established correlations between air quality and wellbeing, and the importance of feedback to raise awareness on aspects of their wellbeing. Drawing on the key issues highlighted in the previous section, below is the framing of a design agenda for developing ambient spaces to support the wellbeing of remote home workers, and plan towards hybrid (and spatially distributed) workspaces. Key areas for development of ambient workspaces include:

- **Actuating spaces**
  Home office can be challenging for physical wellbeing for many reasons. As many participants mentioned, they do not walk much when working from home – i.e. no requirement to commute to work or to attend a meeting in the office etc. As everything can happen in front of a screen (such as remote meetings) their physical activity is reduced. Even if physical activity is planned during lunch break or after the workday, a great deal of movement throughout the workday- e.g. walking from one side of a building to the other to attend a meeting - is missing. This is often combined with the experience of spatial variation – as different spaces in office buildings are made and used for different tasks or social occasions. Battling this, many participants use notifications and planned breaks to get themselves moving around their house or change working spots in their homes (also out of a necessity as there is conflicting space use). The latter often creates complications such as poor ergonomics (when using furniture for office work that is not supposed to be used this way).
  The discussion shifts from providing merely activity feedback through bands, to designing ambient experiences that inherently engage their occupants in a more active

work life in the homes, initiate breaks, and support with body postures while working in diverse spots in the house. Adaptive furniture such as height-adjusting desks or table-desks illustrate such applications; with the problem that they are often bulky, heavy and space demanding [275,363,364]. Lightweight robotic furniture and particularly soft robotic furniture elements and interior artifacts such as smart textiles [34] is an upcoming and highly relevant design agenda for ambient and physical feedback in the workplace. Ambient wok spaces could utilize soft sensors and actuators and actuated materials embedded in interior elements and furniture to support different working postures and movement throughout the workday. Research on soft robotic interiors for the domestic workspace – and for the office space in general – is in an early stage. A few examples of such work such as Proto-chair[93] - an auxetic 3D printed seat that senses changing postures- and Smart-rug[188] – a textile interface that provides feedback for restraining cross leg- illustrate interesting applications of soft robotics but are yet not designed for workspace considerations. Research of soft sensors for posture sensing (see smart chairs for instance) has been widespread; but work on inflatables for posture support[159] is relatively limited; interesting relevant projects is BodyPods [283] and PneuMat [419]– the latter illustrating the development of an inflatable mat to support with infant sleep postures.

- **Organic Transitions**

  As an extension to the above, the challenges transitioning between domestic and work life and balancing different aspects of remote work life in the home have been extensively documented in the findings. Shape changing room dividers can support expanding work and display areas within limited spaces, address conflicting space uses, control light, limit noise, and support transitions between different aspects of work, and between work and domestic life. Example research on inflatables[325] to create interior elements such as soft wall partitions. Apart from research on the actuation effect, geometry and metamaterials for shape change [34]; there is a great potential for soft sensors for controlling such systems. Calm computing research illustrates examples such as textile sliders [264] embedded in chairs - of soft interfaces embedded in furniture providing interactive and adaptative capacity; which can be extended to domestic workplace applications.

- **Calm climatic feedback**

  As the findings highlighted, home office can be challenging in terms of maintaining essential light, noise and air quality levels while effectively managing energy and conflicting space-use. Particularly air quality appears to be difficult in maintaining, as it a latent aspect (often does not come into awareness). Utilizing soft sensors and actuators, passive data processing and the diversity of smart materials and meta materials; ambient workspaces could include passive technologies for user-control of domestic micro-climate. Thermochromics applied on desk-used objects or window blinders or curtains for instance; can be used as a passive and calm display to illustrate deteriorating air quality without dominating attention or requiring a constant checking of one's smartphone or screen. Physicalizing air quality data to create awareness in a non-intrusive and slow way can better support work tasks, provide aesthetically pleasing experiences and support wellbeing. Addressing the experience of air quality, slow and passive environmental responses (see pneumatic elements [237,408,419]) could provide indications of air quality aspects and breathing patterns [407], encouraging a more 'embodied' approach to experiencing and acting on the micro-climate. A relevant project that explored interior elements as air quality displays is Shutters [71]; illustrating potentials of room dividers to act as physical displays for air quality data. Beyond awareness, shape changing physical interfaces can proactively adapt to alter microclimate. The use of SMA wires [240,289] is more recently employed in window blinders to change shape when overheated, controlling the amount of light entering the room [49]. Research on shape changing elements that adapt based on environmental data to adjust climatic conditions - commonly used in façade systems [131,358]- can be further explored for interior spaces and the domestic workspace.

- **Reflective and restorative architecture**
  Light has been widely explored in past research with regards to diverse aspects of wellbeing – including arousal and stress levels [345,373,410], self-awareness and social awareness [285,287,315,410]. Programmable LEDs (see Philips LEDs or Neopixel) provide new avenues for scalable experiences at home while offering user customizability and user control (as many of them support open APIs). With many of the participants using daylight lamps at home office, the use of programmable light to support wellbeing, work tasks and transitioning to domestic life is highly relevant. The quantitative results indicate that utilizing passively collected ambient data to predict wellbeing (valence/arousal/stance dimensions) is not a farfetched idea; proposing a programmable LED system that utilizes data predictions to either create awareness and/or restore wellbeing can be an interesting and meaningful application in home office. Other applications of light interventions can include social awareness (connecting home offices together – see light for social connectedness [285] to create synchrony between remote colleagues and rhythmicity in the workday. Other aspects of restorative architecture highlighted in the findings point towards biophilic design – design decisions that support nature or nature-imitating elements in the office to enhance wellbeing. Biophilic design and biomimicry [276,397]are design agendas often related to soft robotics [36] with many unexplored potentials for interior applications for workspaces.
- **Privacy-friendly and user-driven hybrid offices**
  Ambient workspaces are data -driven spaces, supporting scalability, transferability, and portability of interventions beyond the domestic and towards the hybrid, spatially distributed workplace. As with any smart office building, ambient workspaces should be privacy-friendly; utilizing passively collected data, employing data aggregation, and providing transparent information on what data is collected and how it is used [215]. Home-office has different complexities from open plan office buildings as the data produced is inherently personal (even environmental data are linked to a person's house)[99,257,414,420]. Given that applications for smart homes utilize such personal

data, user's consent should be given for data processing or use takes place outside local spatial/digital boundaries [207,284]. Nevertheless, interesting applications to support wellbeing arise from the distribution of workspaces across office buildings and domestic set up; and similarly interesting complexities for data privacy[68,251].

Ambient workspaces should user-driven and user-controlled. As highlighted in the previous chapter, a level of automation for health and wellbeing purposes in the buildings for work (in their case, smart office buildings) is desirable; still data should support and not replace human reasoning [215]. The case of home offices is not radically different; meaning that participants would appreciate a level of automation in controlling some aspects of their environment. Ambient workspaces should engage in a collaborative dialog with their users, to develop intelligent behaviors with their occupants and not for their occupants; investing in appropriate feedback strategies to create data awareness [216].

Apart from opportunities, creating ambient workspaces has many constraints and limitations; reflecting not so much on technologies but on ethics, privacy, and data accuracy in lived workspaces. As a response to ongoing concerns on privacy and the use of personal data at the workplace, this work focuses on the potential of passively collected data only. Perceptions of privacy and agency in digital enhanced workplaces have been addressed by a previous body of work (see previous Chapter) and have been considered in this chapter.

5.4.3. Three example design interventions for the ambient workspace

To further illustrate how this design agenda can be made useful, I began to elucidate three concept designs (for future development) for ambient home workspace technologies. Each of these draws on different aspects of the design agenda above.

5.5.3.1. Flex-Seats: chair addition for supporting active working.

As highlighted in the findings, achieving the ideal home office is not easy, due to lack of space or conflicts in space use. Reflecting on the diversity in reported needs in structure, variation and flexibility, there is the broader question if a strictly 'fixed' office set-up can work in a 'limited, loose and flexible' environment like the domestic one. Many innovative workplaces already support hot-desking and working in lounge-format offices (see Google Zurich[117]), even active workstations (see the Edge, Amsterdam[118]). The above results of the domestic office in terms of ergonomics, reach and use zones, peripheral aspects, comfort, and positive engagement, frames the following design concepts for adaptive modular furniture. Enriched with ambient sensors (such as proximity, touch, pressure), adaptive furniture can enhance the affective and physical wellbeing of remote workers through supporting different postures and encouraging breaks. Examples of such furniture should have the following attributes:

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[117] https://www.businessinsider.com/google-zurich-headquarters-tour-2018-1?r=US&IR=T
[118] https://www.bloomberg.com/features/2015-the-edge-the-worlds-greenest-building/

- Lightweight, modular, and user customizable; for better fitting to different body types, in and on existing furniture, and within limited space in the house.
- Shape Change and color change using soft robotic elements – e.g. inflation, rotation, folding; actuating for physical activity, initiating breaks, and supporting posture alternation (between sitting and standing).
- Data-driven, Portable and transferable; connection and transferability of data between workspaces. For instance, saved shape-change pattern preferences based on work tasks (data obtained from calendar).

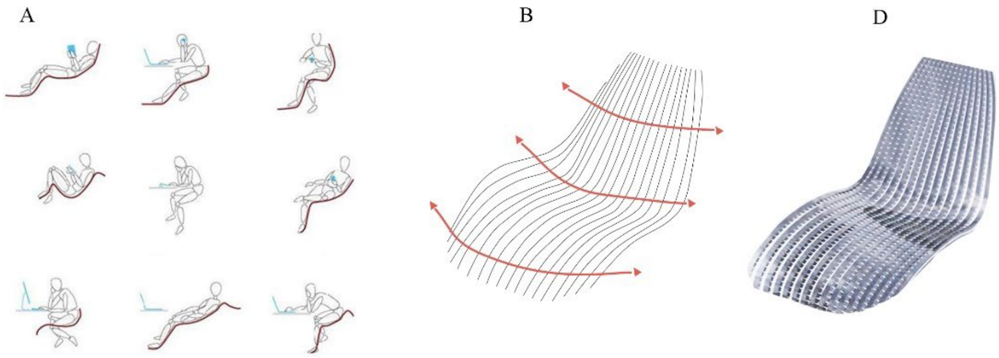

Figure 43: Concept of a sensing adaptive kinetic chair concept for posture management

Figure 44 (A), (B), (D) illustrates a concept of shape changing chair addition/cover mat that supports posture alternation and transitioning to different work and non-work tasks. The furniture senses body posture through textile sensors and moves through pneumatic actuators embedded in fabrics. It syncs with your work calendar app adapting to tasks such as meetings, focus work, creative work and breaks. It allows you to design pre-plan postures and nudges you to change sitting postures with subtle movements.

5.5.3.2. Reflex-Light: Wellbeing- predictive architecture

Considering the participants' interest in mood-reflective feedback in the workplace, and the rich background literature on ambient light [345,410]; I aim to use light as mood-reflective and mood predictive strategy. Many new light products- such as Philips LEDs - enable user-driven ambient atmospheres customizable through mobile apps; creating and storing complex light scenes in different rooms, set timers and scenarios. Many of them have open APIs and embedded microphones, sync with VUIs such as Alexa and dynamically adapt to music. Utilizing open APIs of existing wearable and light devices and processing passive activity, environmental and voice pitch data obtained by microphones, I propose a mood-reflective/predictive light system that supports the following:

- Dynamic adaptation to the ambient natural light of the room, support neutral light coloring or enrichment with different color based on preferences; support task-relevant lighting, and turn off when away.

- Predict mood and provide feedback through temporal changes in color, intensity and rhythmicity of the light to help users become aware of changes in their mood, and help them restore based on preferences.
- Enhancing social awareness and group wellbeing, connecting remote workspaces through sharing aggregated mood data through light infrastructure.
- Control via proximity or touch sensors and wearable sensors.

Figure 45 (A), (B) illustrates a prototype set up including Philips Hue and Mbient[119] sensors (ambient data), using light to reflect and predict mood. **Figure 45 (C), (D)** illustrate experiences in mood reflective spaces. Future work will explore spatiotemporal aspects of light as feedback -i.e. changes in color, rhythmicity, brightness, intensity, scale, synchronous and asynchronous change- in remote workplace with regards to mood awareness.

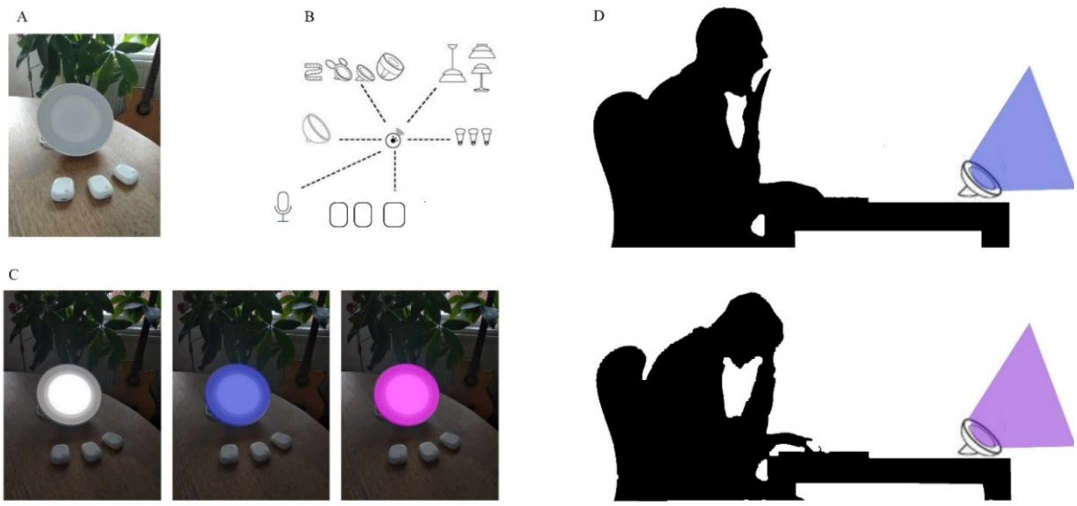

Figure 44: An example of mood reflective/predictive workspace using Philips Hue

5.5.3.3. ActuAir: bio-design for air quality

It derives from the participants' responses that as they focus on their work, they cannot always be aware of all aspects of their surroundings. The study gave them opportunities to evaluate aspects of their micro-climate such as perceived air quality and reflect on their wellbeing. Air quality gave an interesting correlation to valence (positive-negative mood) in quantitative data, being non-present as a documented experience in the qualitative data. Therefore, 'surfacing' air quality data to increase the remote workers awareness on air quality could have a positive impact on their wellbeing and mood.

Some aspects of air quality experience and management are addressed by current research on the workplace [25,422,423]; but many complexities remain unaddressed. The problem of poor indoor air quality is often difficult to solve as air can be more polluted outside, and opening a window can mean increasing noise or decreasing heating. Additionally, much of the research

[119] See mbientLab https://mbientlab.com/

on air quality is limited to CO_2, leaving humidity, air temperature and air flow aside. Design research can focus on developing ambient and physical feedback that surfaces different aspects of air quality; both addressing users' embodied experiences and creating meaningful experiences based on sensory readings. Physical representations of air quality feedback that are closer to the embodied experience of aspects of air quality could deepen awareness of one's body and environment, and how these two aspects relate to each other.

Based on this idea, biophilic design has a lot to offer in developing human-building-interactions for air quality awareness in home office and beyond. Borrowing features from adaptive architecture skins and bringing it in interior architecture [131,157,198], modular pneumatic elements can compose shape changing room dividers, desk barriers and window covers, creating different types of workplace surfaces and enclosures, and visual barriers with display capacity [32] (Figure 46 (A)). Inflating and deflating elements installed in the periphery could support a more embodied awareness of micro-climate while providing a visually aesthetic experience. Such elements could provide physicalizations of ambient air quality data and/or breathing rates of building occupants. Figure 46 (B) is a breathing surface concept – an aesthetic visual barrier coordinating with breathing rate through a wearable, assisting air quality awareness and breathing regulation.

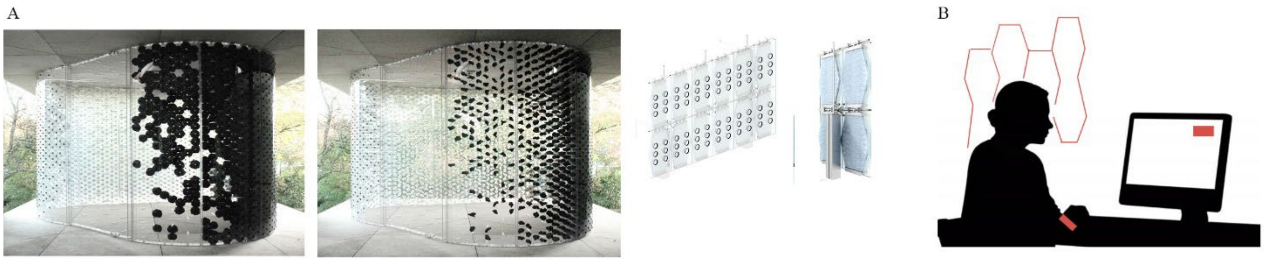

Figure 45: An example of a pneumatic interface for air quality and breathing data representation.

5.5. Limitations

This study has a number of limitations. An overarching key consideration is that data was collected and analyzed during COVID-19 lockdowns, which impacted the study design, set up and choice of methods; with the findings representing an exaggerated image of what the common issues in home office might be. The sample for the quantitative study is relatively small and that these early findings are indicative. Quantitative findings will be validated in future work with a larger number of participants and repeated measurements using sensory readings, and not solely self-reported data. The proposed design concepts that address wellbeing aspects in the built environment are in concept stage. Besides validating findings, future work will focus on developing working prototypes of the design concepts addressed, evaluate these with users in lived-in remote home workplaces, and evaluate and discuss the impact on wellbeing following a Mixed Methods approach.

5.6. Conclusions

This work addresses the experiences and wellbeing challenges of building occupants while working from home (during the pandemic) and provides insights on their experiences with data and their engagement with the domestic workplace. Through a mixed-methods approach, this study establishes correlations between wellbeing, physical aspects and perceived environmental conditions in the domestic workplace; and discusses the impact of feedback mechanisms (wearables and self-reporting) on the wellbeing of remote workers. Key findings were the actions to maximize comfort; the lack of physical activity, and a latent correlation between valence and perceived air quality. Contributing to discourses on Human Building Interaction (HBI) [142,143,209] research, these findings led to a framing of an 'ambient workspaces' design agenda to support the wellbeing of the remote home workers; designing ambient and physical feedback that supports embodied and environmental awareness through passive sensing. I further presented three concept projects as illustrations of how this design agenda can be used. The proposed agenda is composed under the premise of co-creating more intelligent environments together with their occupants and not for their occupants; this is useful to guide future interventions in the context of remote and hybrid workplaces and highlights areas of critical research interest for Human-Building-Interaction and Soft Robotics [36,328] in the Built Environment. Future work will expand on validating correlations, developing working prototypes based on the discussed agenda and will evaluate the impact of the interventions on the wellbeing of the building occupants.

5.7. What is Next?

These two first empirical chapters provide the basis for foregrounding experiences of data in place in two different contexts – office and domestic office – to guide design research that addresses quantification and wellbeing in both contexts. The next chapter- the third empirical chapter - attempts a data-triangulation or the bridging of these two separate research entities, while focusing particularly on experiences and dimensions of wellbeing (RQ1) and data use for wellbeing (RQ2) in both contexts – framing the so called 'hybrid' workplace wellbeing. The next chapter unpacks design concepts around data use for wellbeing in the hybrid workplace together with building occupants; through a co-design workshop with an emphasis on data physicality, soft sensors/actuators and affordances of architectural spaces.

Chapter 6. Co-designing for Wellbeing in the Hybrid workplace.

6.1. Introduction

6.1.1. Research Context

This chapter is the final chapter of Section B: Understanding People in Place; revolving around mapping the experiences of wellbeing of the occupants of a smart office building during a period of hybrid working in May 2021; when they were working both in the office building and at home, and moving in between these two places. The post-Covid-19 hybridity of the workplace is a novel context for HCI & HBI research; it has never happened on that scale, and each workplace deals with it very differently. Numerous technologies have been developed and employed to assist with hybridity in the workplace; particularly tools that bring synchronous and asynchronous collaboration together – e.g. enhanced chat tools in Teams videoconferencing software [217,256] - with hybrid meetings having their own unique challenges and opportunities for research – see for instance works on double robot for hybrid meetings [92,256,318]. With the focus of this work being on the experience of the built environment (physical and spatial dimensions) and relationships with data in it; this Chapter addresses how the hybrid workplace as in the domestic and shared (office) workplace (as places) are experienced by the building occupants of a smart building, to inform future HCI design research that addresses the human-centered aspects of the physical and digital dimension of built environment.

This Chapter has a particular focus on wellbeing for two reasons. First, wellbeing is one of the major concerns during Covid-19 and in the post-Covid-19 workplace; that highly influenced the motivation behind this research. Second, based on findings in Chapter 5; wellbeing is of increasing importance for the building occupants of remote workplaces, with findings pointing towards emerging correlations of air quality and emotional wellbeing (valence). Based on that, this Chapter explores the experience of wellbeing across the shared and domestic workplace; framing studies such that the building occupants' thoughts and concerns around aspects of wellbeing - and particularly environmental wellbeing and air quality – are surfaced, and tied to specific data-use concepts.

In this Chapter, I employ co-design as a research method for exploring the design space around the use of data for wellbeing in the shared and domestic workplace. I use co-design to further engage the building occupants into speculating how their workplace environments could physically use data to support them with emerging wellbeing challenges; creating tangible design concepts using a purpose-made card kit which addresses physical spaces, affordances and data (sensors) for wellbeing. The reason co-design is employed in this stage of my PhD is twofold. Based on previous findings in *Chapter 4 Understanding Occupants'*

Experiences in quantified buildings, the building occupants expressed that data could be surfaced in the building to be made useable as they see value, highlighting the need to be able to be experienced in the building. In *Chapter 5 Understanding the Dynamics of the Domestic Workplace*, findings highlight the importance of feedback mechanisms for wellbeing in the domestic workplace, inspiring towards a framing of a design agenda that addresses ambient feedback for air quality (amongst others); envisioned by the researchers but without addressing the building occupants in any dialog on designing physical ambient interventions. In response to these findings, I made and used a card-kit to further engage the building occupants into materializing their views on data use in the building into design concepts; giving them tools to navigate the design space of physical displays and feedback in the context of the built environment and at the scale of architecture.

Given the nature of hybrid working being in-between two spatial contexts, the framing of this chapter is highly related with the research framing and context of the previous two chapters. This chapter provides a bridging between the findings of *Chapter 4 Understanding Occupants' Experiences in quantified buildings* and *Chapter 5 Understanding the Dynamics of the Domestic Workplace;* validating findings of these two chapters, while further addressing wellbeing-related experiences in both shared and domestic office contexts. Moreover, the chapter provides a bridging with the upcoming Design research chapters through co-design; solidifying the framing of design directions and a design agenda for *human-centered data-rich workplaces for wellbeing* addressed in the two previous chapters.

6.1.2. Research Questions

This chapter responds to:

- RQ1: What are the experiences of the building occupants in the quantified workplace? (RQ1c: How do building occupants experience the hybrid workplace (office and home office) and
- RQ2: How do their experiences inform data use for wellbeing in the buildings for work (RQ2c: How do their experiences inform data use for wellbeing in the hybrid workplace?)

Responding to RC1c and RQ2c, I conducted two (2) exploratory design-led studies with (13) participants in total, who were occupants of a quantified office building, working both remotely and at the office (e.g. hybrid) during May 2021. The first study was an online focus group using a MIRO canvas, that engaged seven (7) participants to reflect on and discuss aspects of their wellbeing (framed following the PROWELL[120] model of workplace wellbeing assessment) when working in the office building versus when working at home. The second study was a co-design workshop with six (6) participants facilitated through use of a custom card-kit[121],

[120] https://www.innovativeworkplaceinstitute.org/workplace-wellbeing-prowell.php
[121] see https://leniamarga.github.io/Workplace-Wellbeing-Toolkit/

which explored novel directions for designing for wellbeing in future hybrid workplaces, with an emphasis on the physical dimensions of interactive technologies.

6.1.3. Research Contributions.

This chapter provides empirical and design contributions to the field of HBI research. In terms of the empirical contributions, it provides insights from the building occupants' experiences around wellbeing during a period of hybrid working; highlighting pressing research challenges for designing for wellbeing in both shared and domestic workplaces, tied with the human-centered development of quantified buildings for work. Key findings highlight conflicting perceptions over air quality levels at home office and in the office building; prompting towards the importance of increasing air quality awareness in both contexts.

This chapter also provides considerations for a design agenda on interventions that address physical and tangible dimensions of interactive technology for supporting wellbeing in the shared and domestic workplace through a co-design activity. Findings highlight novel opportunities for biophilic design in the building for work; relating biophilia and biomimicry with social wellbeing, physical activity and community building in the hybrid workplace. It finally frames design directions for design research that wants to address biophilia in the built environment in the context of wellbeing for the quantified workplace; pointing towards the emerging design space of soft robotics and actuated materials, and air quality/climatic awareness interfaces.

Summarizing, the chapter provides the following empirical and design contributions:

- Responding to RQ1, this chapter provides empirical contributions to the limited number of studies in HCI/HBI research around wellbeing in the hybrid workplace, by unpacking the experiences and perceptions of building occupants in that context.
- Responding to RQ2, this chapter provides design contributions regarding the data collection and use for health and wellbeing in the hybrid workplace; and discusses a design research agenda for the human-centered development of smart buildings.

6.2. Methods

Aiming to map the wellbeing-related experiences of the hybrid workplace, I conducted a focus group with 7 participants as my first study. During this focus group, diverse aspects of wellbeing are highlighted with an emphasis on environmental and physical wellbeing; also validating past findings on remote workplace on air quality (Chapter 5). Co-design is employed in the second study, to engage the building occupants into materializing design concepts that address previous findings on making data visible and accessible in the buildings and creating opportunities to experience data in place (Chapter 4); providing ambient feedback for wellbeing (Chapter 5). As these findings point towards the design of data physicalizations, I needed to invent a way to engage the building occupants into the design space and design language of physical displays and ambient feedback – e.g. use of light, shape and color change as feedback etc. I therefore designed a card-kit to engage 6 participants into the physical interaction design language, and through co-design explore the emerging opportunities for feedback to support wellbeing in the buildings for work (Chapter 5); to provide tangible design directions to support my upcoming design research work. The sections below provide details on the studies that took place, an overview of Co-design as a method, and detailed description of the card kit that was used for the co-design activity.

6.2.1. The custom Card deck design

The purpose of the studies was to co-design with participants with a focus on physical and tangible interactions that address data and wellbeing in the buildings for work. To do that, I designed a card deck I designed and used it for my research. The card deck[128] revolves around four key components: Wellbeing, Sensors, Actions/Interactions and Spaces – including building elements, architectural features and objects in space.

Actions/Interactions cards (Figure 50) provide the connection between Sensor cards (sensory data) and Spaces (workspace elements). Heavily influenced by the notion of affordances [295]– i.e. the quality or property of an object that defines its possible uses (degrees of freedom) on how it can or should be used. Under this lens, the physical properties of the environment invite building occupants towards certain (inter)actions; which were then translated into cards' actions & interactions concepts in order to guide the design of interactive and adaptive architectures, physical interfaces, and ubiquitous embedded interfaces. The Actions – i.e. how the user manipulates spatial features - and Interactions - i.e. how the users-environments interact with each other – cards are left open to interpret on how to use; without clarifying if they refer to an imaginative user that acts according to the concepts stated to cause a desired change, or if the environment causes that change on its own. This has been left vague on purpose, with a view to exploring ideas of control, environmental determinism, and anthropomorphism - of (interactive) architecture – i.e. architecture that leads interactions or actions and becomes the character. The actions & interactions cards explore color and shape change, different aspects of feedback, materiality and temporality of data driven feedback; examples of actions cards are open, shift, assemble, twist, bend etc.; examples of interactions cards are changing color, light, material properties; visual, olfactory feedback etc.

[128] The card kit can be found at: https://leniamarga.github.io/Workplace-Wellbeing-Toolkit/index.html and in supplementing materials.

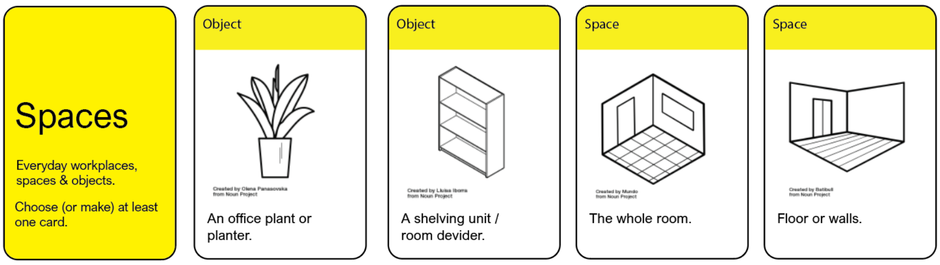

Figure 47: Spaces cards examples (all cards are available in the supplementing materials)

Wellbeing cards (Figure 48) were designed as per PROWELL[129] wellbeing dimensions: physical wellbeing – including physical comfort, environmental wellbeing, physical activity and nourishment; mental wellbeing – including cognitive and emotional wellbeing; and social wellbeing. Key aspects are mentioned under each of these dimensions; for instance, air quality, light, temperature is under environmental wellbeing; noise under physical comfort etc. – but without this being a strict classification. Cards were also left blank for participants to edit as they please; some indication cards were also provided to guide thinking around wellbeing aspects: awareness, improvement control - although these terms were also provided as an indication on the cards.

Figure 48: Examples of Wellbeing cards (all cards are available in the supplementing materials)

In terms of the other two card categories; Sensors (Figure 49) include different types of passive sensors. Apart from the data sources collected, the physical form of the sensor is mentioned – e.g. flat sensors, wearable sensors. Spaces cards (Figure 47) include sketches of rooms, architectural elements and objects; with blank cards provided to give the participants the option to sketch their own. The card deck also provides 'Inspiration' cards (Figure 51) which served as diegetic prototypes; illustrating potential future technologies as outcomes of the card deck, to further trigger the participant's imagination.

[129] https://www.innovativeworkplaceinstitute.org/workplace-wellbeing-prowell.php

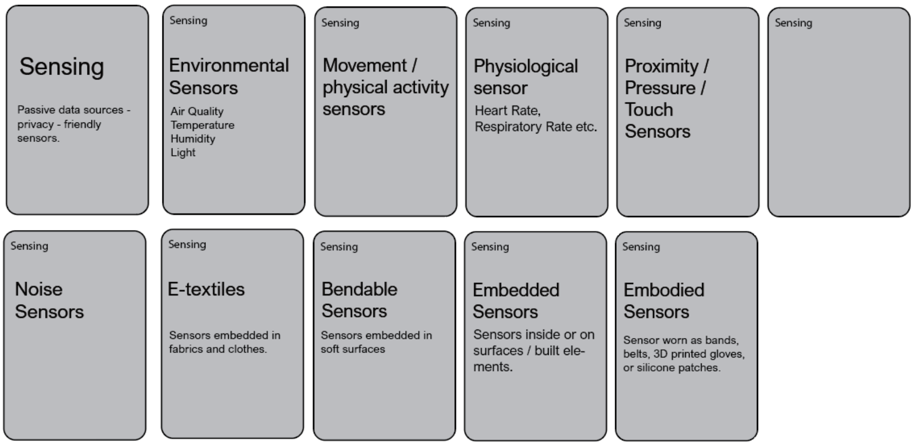

Figure 4950: Sensor Cards (all cards are available in the supplementing materials)

Figure 51: Action/Interaction Cards (all cards are available in the supplementing materials)

In total, the card deck[130] included the following card categories: Wellbeing, Spaces, Sensors & Data, Actions &Interactions, and Inspiration Cards. The use of cards by the participants was supported by the researcher as facilitator and the provision of additional templates to place the cards (as described in the following section).

130 The card kit can be found at: https://leniamarga.github.io/Workplace-Wellbeing-Toolkit/index.html and in supplementing materials.

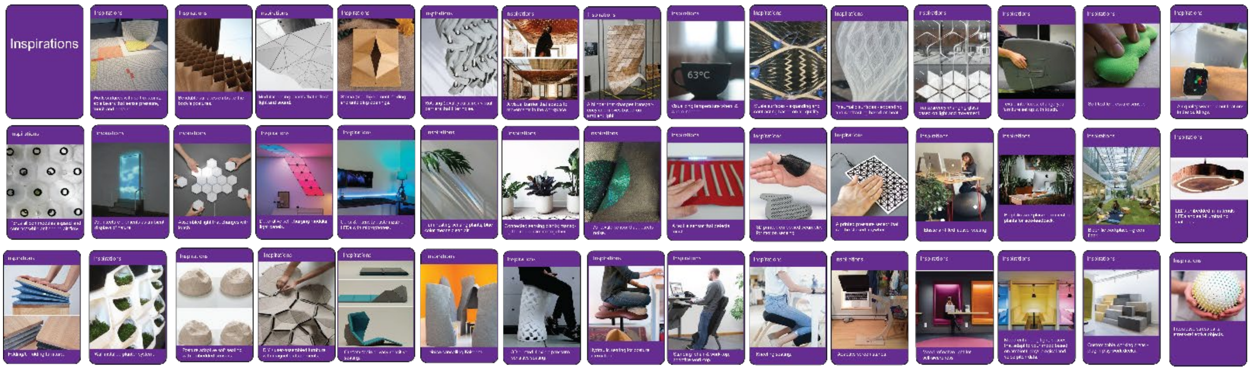

Figure 52: Inspiration cards (all cards are available in the supplementing materials)

6.2.2. Studies Description

The following studies were conducted remotely during May 2021, using MIRO and Zoom. Both studies were designed and facilitated by the researcher (myself); and were video recorded and transcribed using Otter.ai.

- Study 01 “Wellbeing in the quantified workplace”; a focus group workshop (60min) exploring aspects of wellbeing in the smart workplace. Seven (7) participants, occupants of the same sensory-rich workplace were introduced to PROWELL wellbeing dimensions (5min) through a MIRO board. They were asked to identify positive and negative experiences (pros & cons canvas) when working from home and in the office, with regards to a) environmental wellbeing & physical comfort – i.e. air quality, temperature, light, noise, ergonomics; and b) emotional & social wellbeing – i.e. autonomy, control, personalization, social connectedness. After a 20min exercise where participants placed sticky-notes with their thoughts and concerns, I asked them to further reflect on some key ideas that stood out (15’). The workshop was finalized by prompting participants to consider what data would be meaningful to collect to support wellbeing interventions in the workplace; allowing them to also express final thoughts and considerations (15’).

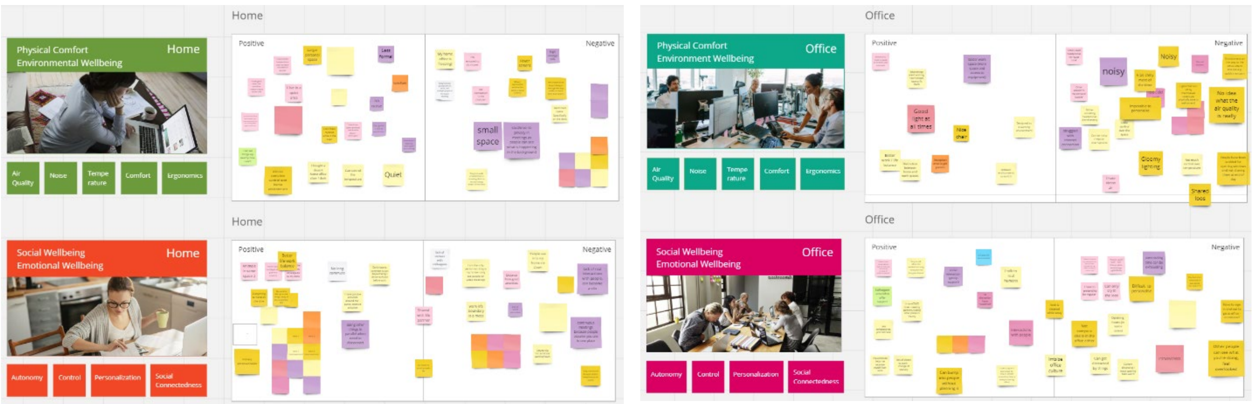

Figure 54: MIRO boards during Study 01

- Study 02 “Co-designing for wellbeing in quantified buildings”; a co-design workshop (90min) with six (6) participants, occupants of the same smart workplace building. Participants were introduced to the PROWELL model (5min), the custom card kit described below and how to use the cards (5min) through a MIRO board. They were left to explore the card categories - spaces, sensors, wellbeing and action cards - on their own and choose some that resonate with them following the card deck rules (10’). The rules included selecting 1-2 wellbeing cards, 1-2 sensor cards, 1-3 spaces cards, and 2-5 action cards. Then participants were requested to individually form a scenario of an interactive experience using their cards at a dedicated canvas space; and use post it and notes to make it as clear as possible to the rest of the participants (15min). Then the participants were divided into groups of two (2) and were asked to choose one of the scenarios and work on it together for another ten (10) minutes. After a short break (5min); they were then given 20min to work in groups to produce a design concept of the interactive experience described in their group stories. The inspiration cards were also openly available to them for inspiration; but were not allowed to actively use it in their scenarios and designs. They were asked to sketch, use images, illustrations, annotations and post it to create their designs on a dedicated canvas. In the final 20 minutes, participants talked about their individual and group scenarios and their design concepts.

Figure 55: Example of a group scenario and design concept – P03&P12

6.2.3. Participants

Participants were recruited from occupants of a smart office building; all working in the same workplace pre-pandemic, remotely during the pandemic, and currently returning in hybrid mode for the time being. The majority of them had relevant knowledge in computer science/ information technology and HCI/interaction design disciplines; but none identified themselves as knowledgeable about the IoT, adaptive architecture and/or shape changing interfaces research spaces. The card toolkit was designed with that in mind, to establish a common design language to help them ideate and explore the design space of shape-changing and physical interfaces in the context of integrated wellbeing in the built environment. Participants from workshop 01 were encouraged to participate in workshop 02; although that was not an essential prerequisite as contextual information was provided in both workshops.

Table 4: Participants

Participant Number	Study	Expertise	Gender	Age
P01	S01	HCI/Digital Public services	M	>40
P02	S01	Project Manager	F	30-40
P03	S01 & S02	Computer Scientist	M	<30
P04	S01	HCI/Public Health	F	30-40
P05	S01	HCI/Nutrition	F	30-40
P06	S01	HCI/Digital Inclusion	They	<30
P07	S01	HCI/Digital Inclusion	They	<30
P08	S02	HCI/Behavioral Scientist	M	30-40
P09	S02	HCI/Digital Democracy	M	30-40
P10	S02	HCI/Education	F	>40
P11	S02	HCI	F	<30
P12	S02	HCI	F	<30

6.2.4. Data Analysis

For each workshop individually, text data from the MIRO boards (e.g. sticky notes, text notes) were exported (excel format) and combined with the transcripts of the video recordings. For the co-design workshop, the canvases of each individual scenario, group scenarios and concept designs were exported as images for the purpose of dedicated visual thematic analysis [263]. The text data (notes + transcripts) were qualitatively analyzed first for each workshop individually to produced key themes. Data from workshop 01 were thematically analyzed, and data from workshop 02 were subject to both thematic analysis & visual thematic analysis [46]. At a second round, data from both workshops were then thematically analyzed together, to produce the themes as illustrated in the results section.

6.3.Findings

Following a thematic analysis, key themes are presented below discussing the office building and domestic office together. The themes highlight wellbeing aspects through emphasizing participants' considerations around control and boundaries in both spatial contexts.

6.3.1.The perception of control at home and in the office

The perception of control over one's environment as a key element of wellbeing is a theme that came across particularly throughout W01, illustrated in quotes such as "*(at home) I control the temperature and can wear a blanket if I want to (P06)"; I feel safer & better at home - I feel in control at home (P01)"*. This refers *to* the perceived ability to control aspects of the environment and having the 'choice of action'; which is perceived as a key positive aspect for wellbeing besides the difficulties that the home-office might present. Many participants expressed this theme in different ways- i.e. home office 'feels safer' because they feel they are in control whereas the office buildings 'feels unsafe' – pointing out the ability to change the office set up and environmental conditions as they wish -*"(at home) I can set up things exactly as I want "; "(home office) almost complete control over home environment"; "(office building) little control over the space"; "(office space) impossible to personalize".* Control was broadly linked to the ability to customize and personalize one's environment, but also with regards to managing personal boundaries; *" (office building) I have to explain my boundaries to new people repeatedly e.g. don't creep up behind me" .*

The feeling of control is often described through emphasizing on physical and tangible actions – e.g. *"opening a window for fresh air"* - whereas the restricted ability to physically customize in the office building contributes to feeling of *'less in control, less safe'*. The perceived lack of control in the office is enhanced by both the limited *ability* to physically act, but also, the perceived inaccessibility and underutilization of the collected data by the building occupants; *"about air quality - Really, yes there's lots of lots and lots and lots of data, but actually nothing to tell you what we want to know (P01)"*; also in quotes highlighting the importance of involving the building occupant's as part of any technological intervention "*You cannot really control too much the actual solution ...it is just not really solving a problem because, once you decide to open your window, you end up having contamination from the outside (P03)";*

The feeling of control in the domestic office sometimes stays merely a feeling; as often the reality of the domestic office includes negotiating with others. This was highlighted P06 quote on the embodied perception of climate is very different from person to person and that using standards is a useful strategy to equalize these differences *"... my partner and I have very different experiences of temperature ... I don't necessarily have complete control (at home), there has to be in negotiation when changing anything. ... I am outnumbered in terms of my preference so usually it just ends up staying very cold and I use a blanket.... I find the temperature in office spaces is usually fine for me, like the sort of group- consensus averages out to something that at least I can tolerate and I assume a lot of other people can tolerate (P06)".* More quotes illustrate the rather complicated reality of the domestic workplace such as the difficulties on achieving ergonomics in limited space *"(home office) restricted space on the desk"; "(home office) only so many good places to work and multiple people in the house working*". Adding to the this, some referred to the difficulties managing air quality at home; highlighting how aspects of scale and infrastructure might impact control. *"I live in a small studio and I often feel that air gets super dry and stuffy for me, especially like at night and then waking up the next day to work. I feel like it's (home) not a very healthy environment...the office* *during the day; because it's more spacious, bigger space, more rooms to go around, I feel the air quality is circulating in a better way; and, I don't know, I feel the ventilation system might be a bit better.... most people get humidifiers and things like that at home; that's something for example I don't need to think about when I'm in the office.* (P04)". This quote highlights the key underlying issue while working from home which is that the control and management of environmental wellbeing becomes one's own responsibility, which, although desirable by the majority of users (the feeling of control) can become a complicated task depending on available infrastructure – i.e. windows, air ventilation system - outdoor air quality, and other aspects such as the person's awareness of air quality levels and ability to act – which can add cognitive load while working.

6.3.2. The rhythm of the workplace

The quotes below summarize the agreed perception that the office provides work-life with a rhythm and a coherence, a balance between the domestic sphere and work life. This extends to a number of domains, including collaboration – getting support from others – physical activity and work-life boundaries.

Unpacking these further, a common agreement was that home is a quieter place to work than the office *"I live in a quiet area"; "(in the office building)I often need headphones for quiet time"; " (office building) noise-cancelling headphones are necessary".* Participants felt more in control of noise disturbances at home; which was further discussed in the context of the social life and social interactions – and interruptions - in the office versus at home. Many noted the lack of ambient noise at home also meant lack of social presence and social interactions with colleagues; which, provides rhythm in the workday (2/7) *"(home office) easy to slip in antisocial working hours"* whereas *"(office building) easy to tell when I've worked too long – everyone else has gone home";* also benefiting from spontaneous and serendipitous interactions with colleagues; *"(office building) colleagues are around to offer support"; "bumping into people"*- which is missing from home working.

Physical activity was mentioned by a few in the context of utilizing work breaks or time in the morning/afternoon instead of commuting to and from work. *"(home office) I have more time (no time spend on commuting)"; "(home office) I can go for a run during lunchtime"; "I don't have to commute so I can do dance workouts/journalling before work"*. But some expressed that although the home office provides more time for physical activity, a lot of personal reminders are needed to prompt towards moving; whereas, this comes natural consequence when working in the building *"(home office) I forget to walk around (I have a standing desk so I'm not sitting down all the time)";"(office building)it is essential to move around to facilities and commute".* The social life of the shared workplace creates the prompts and nudges for moving around, which lacking at home; where a lot of personal reminders and motivation is needed.

Some others referred to the overall office space layout and the variation of spaces to work as also contributing to having a more healthy and physically active work-life; which is not the case at home "(office building) different environments to work in"; "(home office) only so many good places to work and multiple people in the house working". The availability of separate places to work was further linked with maintaining healthy work-life boundaries; "(office building) offers distinction between home and workspace"; "(home office) work-life boundary is a mess". On the latter, P07 commented *"... especially if it's a hard day at work, it's nice to have somebody trusted literally right there but then sometimes ... work and personal life becomes even worse, like the lines between it.(P07)"*

6.3.3. Active, Collective and social dimensions of Biophilic Design

Co-design workshop (S02) highlighted the need for enhancing nature in the built environment; illustrated in all 9 participants' scenarios where plantings were present. All 9 participants' scenarios (6 individual stories, and 3 group stories) involved a reference to bringing nature to the workplace. This is a key finding with regards to the importance of nature for wellbeing in the shared and remote workplace; which was further linked to different aspects of environmental, physical, emotional and social wellbeing throughout the scenarios, pointing towards novel directions in designing biophilic environments. In 7 scenarios, nature appeared as 'instrumented'- i.e. with sensing and actuating capacity - creating awareness on the plants' needs, prompting towards a certain action taking place -e.g. caring for the plants - or connecting remote and hybrid workers around caring for the plants. In 6 scenarios, nature was linked to social wellbeing – i.e. nature providing cues to social connectedness or to prompt towards seeking social interactions – emotional wellbeing -i.e. having a restorative capacity, restoring from stress - and physical activity – i.e. prompting people to move or go out. In 6 scenarios, nature has directly linked with improving indoor climate of the workplace; with indirect references to air quality aspects. Key relevant points from the participant's scenarios are further illustrated below.

In P10's and P11's scenario, nature was primarily linked to maintaining a healthy micro-climate; with P10's scenario addressing biophilic design translated as bringing more plants in the offices and nature used as a restorative strategy. Naming it as "active but calm" workplace, P10 suggests that IoT- enriched plants can be automatically taken care of, *"It is important to have a natural space that helps you feel relaxed when working ... plants supported with embedded sensors that respond to temp. humidity etc. and water according to their needs (P10)"*

P08 & P09 address social wellbeing (social connectedness) and physical activity (movement) under the theme of biophilic environments as social and active restorative spaces. P08's scenario evolved around biophilic environments that respond to the lack of physical activity through ambient movement, visual and olfactory feedback. P08 imagined that instrumented plants - an interior green wall with embedded technology to be able to actuate based on ventilator fans – will move and smell to provide feedback when limited physical activity is detected; producing a calm yet activating effect that hopefully prompts people to move. P08 also referred to identifying high stress from motion and heart rate sensors, and using the same intervention as a stress restorative technique – i.e. when high stress is detected; indirectly linking stress with lack of activity, and physical activity as stress-restoring. Although not directly discussing aspects of air quality improvement associated with bringing nature in, P08 viewed air flow and air circulation as important aspect or indoor air quality and environmental wellbeing; and potentially a feedback mechanism. Summarizing, P08's scenario addresses novel directions for biophilic design using instrumented plantings as actuating/shape changing interfaces that utilize air flow to produce feedback such as ambient movement, smell and imitate the feeling of freshness of being outdoors.

Figure 574: P08's scenario on augmenting nature. *"The idea of augmenting nature with actuation; putting a ventilator behind the plants in the office that would activate specific moments based on data and create some movements around the plants, have ambient movement created and get the smell of the plant. I had the idea how to do this, based on a motion sensor, based on whether you don't move much or are stressed out. ... there's this knowledge about frequency range of physical activity and heart rate, for example, frequency of movements; but it could also be taking this down to heart rate variability ... if you move too fast or too little it's out of the pink noise range. ... basically, the idea was, if you if you provide that motion and ventilation, it can get more relaxing. And the other day idea I was thinking a bit in the same direction ... a green wall that can move (in the same way) and create a sense of motions with plans. The question is how do you connect actuation with sensing…(P08)."*

P09's scenario also involved physical activity and social connectedness; with more references to the hybrid workplace as it is *"important (for wellbeing) to increase connection with the external world and the others around you even if you are not located in the same space".* P09 envisioned that the environment can nudge people get out and get together through a projection system that utilizes doors and windows surfaces turning them into views to the nearby parks when there is very little physical activity (detected through motion sensors) or increased stressed (detected through physiological sensors) in the workplace. P09 did not elaborate on how the stress can be detected; but similarly to P08, they speculated that a combination of activity & physiological data can provide insights on stress. "*Windows/doors in office have movement sensors that will monitor activity; if there is no physical movement for some time or physiological sensors note an increase in stress in the office, it will activate a door art installation. On activation, the doors & windows will project a memory of a favourite place/event that you are fond of. At times that little physical activity is detected in the office, projections will be activated on the door.... The projections/visualizations act as prompts to encourage workers to explore surroundings...(P09)"*

Figure 58: "T*he idea is to capture the moments where and when it's actually too quiet in the office or around you and motivate people in those moments to seek a place of social interaction outside […] so we're thinking to have different scenes projected - like a 'at a park scenario', and so what we wanted to do is to project on windows pictures of the park where people sit that can help people remember oh yeah I should go out and go there and I'll feel more connected again; and give a sense of being there. This can also connect to motion sensors - if it is very little activity in the office which could be sensed by motion sensors - projections can happen again. (P08)";* P08 & P09 group scenario and sketch.

The group scenario between P08 & P09 ultimately brings in elements from both scenarios, utilizing the projection idea – i.e. bringing nature in the buildings as a projection – and utilizing architectural elements as calm displays. The system starts when too little physical activity or low occupancy is detected in the office building; prompting people to go outdoors and get social. In their scenario, social wellbeing and physical wellbeing are connected to bringing nature in the office; bringing a new angle to biophilic design. For P08 & P09, nature and green space indirectly support social interactions; which is highlighted in the group scenario. P08 & P09 referred to motion sensors, abandoning the use of physiological data as potentially privacy threatening. Their sketch provides interesting avenues towards further investigating materiality, transparency and projection techniques in using architecture as display. In their sketch, they pointed towards using windows and walls as calm displays; describing that images of nature are slowly appearing and disappearing in the background. Their scenario provides interesting avenues for biomimetic design interventions, pointing towards further exploring projection as temporal feedback together with architectural features, materiality, color and transparency.

P03 & P12 address social and emotional wellbeing, as well as healthy nutrition. P03's scenario touched upon biophilia as well as nutrition; suggesting horticulture for the office –edible instrumented plants such as spices and an IoT system that organizes a community of building occupants in caring for them.

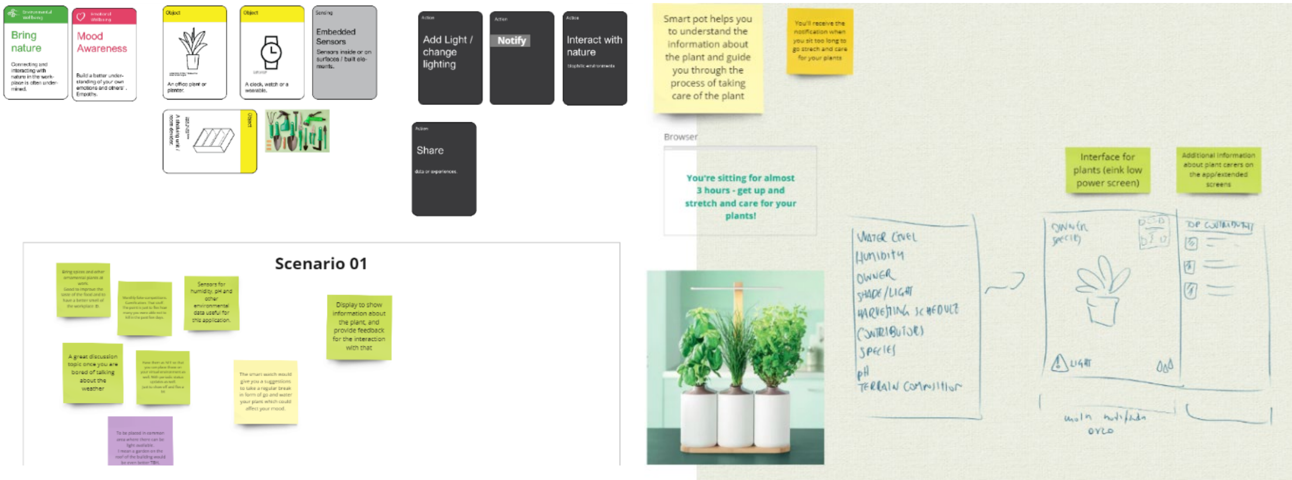

Figure 59: As described by P03 *"adding plants to the environment that we are working in, some at desk and some shared in the building […] generate a better collective mood to your virtual environment of work office, giving a better space to spend time in, and have a break from the routine in front of the screen. And the idea connected to this, to introduce this kind of spaces, you are suggested to go there after spending some time in front of your computer; or you have reminders to just go take a walk and care about the plants.[…] These plants exist also in virtual reality; they are integrated in virtual spaces we well, so that you can actually have same plant in real life as tokens to your virtual space. […] we can also integrate smartwatch notification so that we can actually know when/which plants are going to die, and also to include a social dimension in it, so that he can actually have our peers involved in helping plants surviving so. If you see a plant (belonging to anyone) which is going to die, you can give it water and your name will be written and get rewarded (tokens) virtually […] You will also have access to information about the plant species, about the owner, and all the kind of environmental conditions which are needed for that plan to grow well. There are sensors placed in the plants which are going to help you knowing if water is enough, if light is too much etc."* P03 on P03&P12 group scenario and sketch.

P03 & P12's group scenario further evolved around P03's scenario. In their scenario, they connect nature in the buildings with healthy breaks from work and, indirectly, physical activity and movement in the buildings. Their scenario provides an interesting social dimension in the design and maintenance of biophilic environments by the building occupants. P03 & P12 envisioned a virtual and physical natural environment and a hybrid (shared and remote) community of building occupants that cares for and maintains it. Their scenario addressed elements of gamification to foster engagement, environmental sensors to guide plants' care and visual feedback mechanisms– they referred to screen and wearable notifications.

6.3.4. Data perspectives: what data should be collected and shared for wellbeing.

In workshop 01, Participants briefly discussed their views on data collection for wellbeing in the building. P06 suggested that although the building collects a lot of data some of which can be indirectly relevant or input to assessing wellbeing; there is no data collected directly linked with the self-reported wellbeing of the building occupants, which means it is hard to validate any data insights or make decisions.

"When I think about the data that the that our building specifically collects ... I see a lot of data that might input into the well-being of the people inside; but there's no data on the actual well-being of the people inside so it's like we've only got half the picture and maybe that's why the data from our building doesn't get used in decision making a lot necessarily ...A bit skeptical about how useful that kind of quantified moods data is. But I guess it's better than nothing. There's potentially something to change in the way you manage the building; (not) collecting these vast amounts of very complex pieces of data that aren't necessarily directly related to the actual meaningful output, which is the people in the building.(P06)"

This lack of data 'from both sides' in order to make assumptions- meaning both from the building's sensors, and from people's experiences– was also noted by P05 *"For example, with the temperature, there is one thing about collecting that data about the temperature currently in the space; and then, also about how people feel.(P05)"*. P06 referred to data for wellbeing as mostly data on mood or emotional wellbeing; implying that, to their understanding, that is the most appropriate for assessing overall wellbeing in the building. P06 also suggested that for such wellbeing data, active (non-passive) data collection which requires the building occupant's active input might be more appropriate and privacy friendly – as it will require the building occupants' active consent and participation – while emphasizing on making data collection process as simple as possible.

" ... for well-being data, you need input from the person more or less, and if it's something complicated people just won't do it, and then you won't have data anyway. ... something like a button on the door on the way out, did you have a good day at what today. ... I would describe myself as more privacy conscious than the average person, but I think that's possibly true of many people who work in the building. So, in the context of that building, the limit for me is explicit user opt-in every time data is collected.... for me that would be like the person has to press the button, rather than passively collecting data.(P06)"

P06 suggested that active, targeted and on-the-spot data collection for wellbeing purposes is more appropriate and privacy-friendly than continuous passive data collection. But they also expressed their doubts on how meaningful mood data is overall. P02 also added on this statement. *" If you gave me to rate, whether I'd had a good day at work - but my mood is sometimes bad because of the work, but it might sometimes be for a reason that was completely not related to the work, and it would be affecting my work day and I would still be making a judgment on my well-being in my work day but it wouldn't necessarily always be due to the work environment.(P02)"*

Beyond emotional wellbeing, P05 referred to physical activity data for wellbeing purposes; stating that they found data useful if they are collected and surfaced for their own awareness, but not by the building – as they perceived that this might potentially mean loss of privacy. P05 also talked about temperature in the same way with P06 – pinpointing that it will be interesting to collect both the actual temperature data and data on how cold/warm people feel-but again, this data should be surfaced to the building occupants and not owned by the building.

"I would say that I think, for example in terms of well-being at home, I find it I'm not moving enough. At the same time, I wouldn't want, for example, this data to be collected by into building, like, for example in the office ... but personally for myself, it would be maybe quite useful to have the data like oh you're actually haven't done that much activities, just as a reminder (P05)."

Emphasizing on the point of appropriately communicating data to the building occupants, P01 referred to the office space as highly data-rich but viewed data as underutilized and unreliable. P01 stated that it doesn't clearly communicates relevant information with regards to air quality and it doesn't do anything with the data to improve it. *"About air quality - Really, yes there's lots of lots and lots and lots of data, but actually nothing to tell you what we want to know. I feel safer & better at home - I feel in control at home. (P01)".* Other participants pinpointed that the building occupants share responsibility in regulating air quality *"people have been scolded for opening windows and not closing them at the end of the day"; " You cannot really control too much the actual solution if you aren't installing some pretty huge filters for instance (for air quality) and honestly ...it is just not really solving a problem because, once you decide to open your window, you end up having contamination from the outside.(P03)".* Data and building infrastructure only solve a small part of the issue - *as* the last quotes highlights - a solution that does not take the user's behaviors in-place as well as the broader environmental conditions into account often fails to meet its purpose.

In the co-design workshop, different perspectives on data collection for wellbeing were surfaced. The use of environmental data was present in most of the scenarios – see P03, P08, P09, P10, P11 – combined with the presence of plants; used to sustain a healthy micro-climate for the plants in the office. The use of environmental data was broadly met with zero concerns over privacy.

In four scenarios, the use of motion data was present as a way to assess stress levels and lack of physical activity – see P08's and P09's scenario (Figure x). *"I had the idea how to do this, based on a motion sensor, based on whether you don't move much or are stressed out. ... there's this knowledge about frequency range of physical activity and heart rate, for example, frequency of movements; but it could also be taking this down to heart rate variability (P08)"*. This aspect is interesting; highlighting differences between views of participants in the focus group and co-design activity. In the co-design, the participants seemed to be somewhat concerned about the collection and use of health data to assess wellbeing in the workplace, but still choose to speculate on potential applications. P08 & P09 chose to consider less privacy threatening personal data such as motion and physical activity data – and only potentially heart rate data- to assess emotional wellbeing.

Three participants appeared with no privacy concerns, envisioning the targeted use of physiological data to assess and restore wellbeing. P12's scenario focused on assessing emotional wellbeing and fatigue through passive sensing, providing ideas on a restorative environment that utilizes light and auditory feedback to restore building occupants *"my initial idea was about mood awareness and how to how to actually know when you're tired ... I was thinking about embedding sensors in a keyboard and mouse, and it would be measuring heart rate and respiratory rate to assess fatigue ... when the system detects that the individual is tired or disengaged, light can be adjusted or music can be switched on ... the mouse can vibrate."* P12 also mentioned accumulated data could be analyzed for future predictions on fatigue. P10's scenario suggests that all physiological signals collected through wearable bands should be constantly analyzed to provide with suggestions on when/how long to have a break and what to eat during work "keep track of your body status, blood pressure, temperature, sweat levels, drinking and eating schedules and movement (P10)." including the design of furniture that "would enhance my posture and reminds me to move ... ". P11 similarly moves within the same direction, envisioning a space that monitors everything with limited privacy considerations. *"... I have sensors that tell me AQ, temperature, humidity and physical activity (P11)"* but it is also able to detect the distances between people on screen. P11 indirectly envisions an indoor localization system where all the building occupants' real time locations are known and the distances between them can be dynamically calculated. According to P11, this "people distances" data can be displayed on a big screen and provide visual color coding to notify other users of the space how empty or full the space is and how far other users of the same space are located. *"Particularly during the pandemic we need this data. All this will be showed on a screen in public, so I can easily see that and I also want to share the data collected the data. (P11)".*

Beyond data collection and privacy considerations, the above scenarios illustrate views on public data sharing in the workplace; highlighting the importance of data awareness. P10 & P11 group scenario viewed aggregated data sharing as a way to support wellbeing awareness in the workplace; linking the embodied experience of wellbeing and environmental aspects through data visualizations. In their group scenario, they suggest that the visual representation of key environmental, physiological and physical data in the workplace can provide avenues to the building occupants to assess their wellbeing. Environmental, physiological and activity data were presented in three distinct groups; following a green-blue-red color scale which provide an aggregated measure of environmental, emotional wellbeing and physical activity for the workplace.

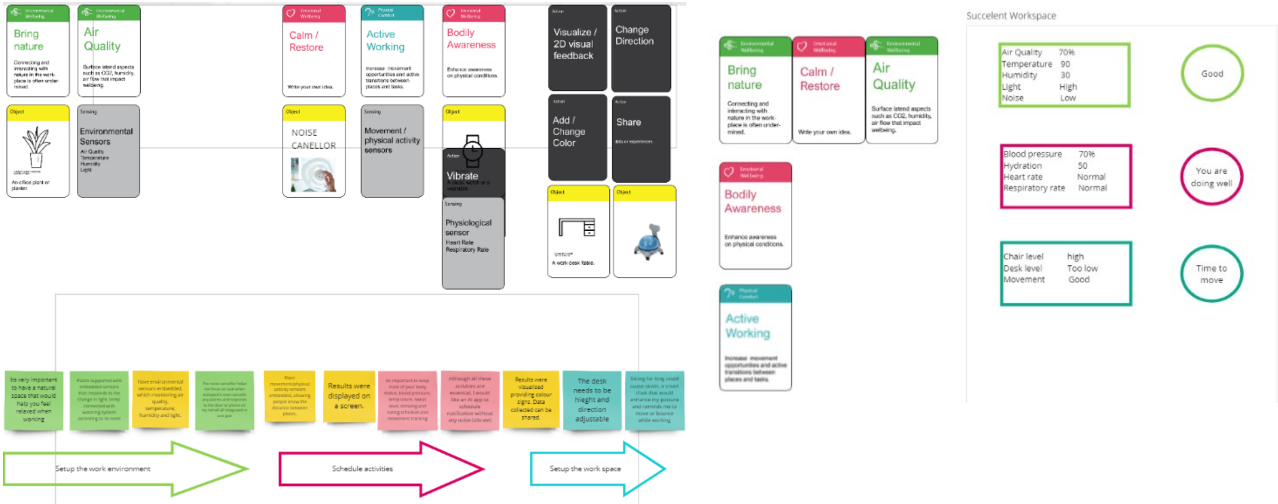

Figure 60: *"We talked about air quality/environmental data, can talked a bit about our design with the smart bands and visualizing on a display in 3 colors[…] For air quality green means good and red means bad; we have three was to feed the data - one is a display that was telling you this, the second way is surfacing on the phone and third a smart watch display […] The idea is basic at this level, you are good or not. we used a lot of a lot of data sources here such as temperature humidity light noise, details to the body heart rate, hydration and respiratory rate and physical activity while working and show if the levels are high or low. (P11)";* P10 & P11 joined scenario and design. As P11 explains, they stayed focused on discussing on what data sources they will (over) consume to produce a highly monitoring office rather than the feedback design provided by the environment.

6.4. Discussion

Below, empirical findings related to wellbeing and data experiences and concerns are summarized in the context of validating past findings of Chapter 4 and Chapter 5. Key design-relevant observations are discussed together with past findings and design-oriented contributions, to solidify future design directions and next steps for Design Research chapters.

6.4.1. Designing for the Perception of control at the shared and domestic workplace (RQ1, RQ2).

Findings suggest that perception of control [99,251,260] is a key aspect of wellbeing in the shared and domestic workplace; therefore, the design of technological interventions should focus on supporting control in different levels **(RQ1)**. The findings illustrate that perception of control is manifested through the potential to manipulate physical space, but it can extend to control over climatic aspects and with regards to personal boundaries [50,176,350] **(RQ1)**. The analysis highlights physical manipulation as key to forming perception of control -e.g. opening windows - which points that the design of appropriate technologies could engage with physical and tangible interactions [5,10,153,156,298] **(RQ1).** In terms of the social dimension of the workplace; control was linked with the ability to negotiate – i.e. quotes on negotiating temperature in the workplace, or negotiating boundaries with colleagues [38,124]. Speculating on the design of technologies to support wellbeing in the shared and domestic workplace context; examples could include physical and tangible feedback systems to support control over personal boundaries in the shared workplace - for instance, tangible interactions and adaptive furniture to foster informal and formal interactions and create boundaries in the shared workplace or at home office [5,121]; or physical interfaces to negotiate environmental conditions such as temperature [70] **(RQ1)**. With regards to the first, see Kirigami Table by Grønbæk et al. [137,139], or shape-changing work by Takashima et al. [363], or Waddlewalls by [275]; yet there are very limited examples of such work that are suited for a domestic or hybrid context where space is limited and portability is a key aspect. With regards to physical displays for climate and environmental wellbeing [10,70,156], ThermoKiosk [70] is an example of physical/tangible interface for negotiating temperature in the workplace; such interfaces could be further explored with regards to aspects of air quality and noise.

Adding to the above aspects of control (physical manipulation and negotiating boundaries), perception of control is extended to data accessibility, useability and awareness [108,124,215] **(RQ1).** Findings address the underutilisation of collected data in the shared workplace for the purpose of wellbeing and the lack of awareness on what the data actually means for wellbeing **(RQ2)**- e.g. the quotes on air quality data that *actually tell you what you want to know*. Such findings point towards surfacing collected data to the building occupants in ways that they can make sense of it and use it to make decisions for their wellbeing in the building [124,215,231]; confirming past findings from Chapter 4. These findings reinforce the discussion around designing customizable physical and tangible data interactions to increase data accessibility and data utilization for building occupants in the shared workplace [156,422,423]; enhancing the sense of control over their environments, increasing awareness on aspects of wellbeing (such as air quality, noise, environment etc.), and supporting relevant decisions in the building [48,61,215]. An example web application that addresses the above is a visual interface of environmental aspects in the workplace[138]; yet, as results point, it would be meaningful if such data visualizations are surfaced publicly in the building to increase in-situ awareness [238,335]. These design directions are further solidified through the co-design session and are further discussed in the next sub-sections 6.5.2& 6.5.3.

The domestic workplace is highly customizable, but as a result, very heterogenous, and its suitability as a workplace often heavily depends on the building occupants' awareness and action[216]. As the above quotes suggest, remote workers require support from feedback interventions to obtain awareness of different aspects of their environment and wellbeing – such as air quality or the lack of physical activity **(RQ2)**. The results particularly highlight the importance of feedback for environmental aspects – for instance, air quality awareness [71,83,104,422] - social connectedness – see projects that utilize light to bring collective rhythmicity in the shared workplace and connect remote workers [85,285,345]- and physical activity – see [82,114,287,315]. These findings confirm past findings from Chapter 5; pointing towards an emerging design space for physical/ambient feedback for workplace wellbeing, with a focus on aspects such as air quality and physical activity **(RQ2)**.

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[138] https://usb.openlab.dev/

Summarizing, the feeling of control that is manifested through the potential to manipulate physical space at home can guide the design of awareness technologies for the office. Design dimensions of perception of control include technologies that provide tangible control of physical and digital boundaries – e.g. what is collected and where, and being able to see, understand and actively engage with data collection and use – technologies to negotiate with others through data – involving negotiating environmental aspects and sharing data amongst selected others - and data physicalizations and visualizations for latent environmental aspects – e.g. bringing air quality to awareness. These findings validate past findings in Chapter 4, highlighting the importance of design research on physical & digital privacy and data control in smart buildings [5,153,284,298]; with co-design activities solidifying design directions for data physicalizations that will be described in the next subsections. The highlighted discussions on air quality illustrate the increased post-COVID-19 interest for the underlying complexities of managing air quality and associated wellbeing; prompting towards designing for air quality awareness in both the domestic and the shared office– as per findings in Chapter 5. Physical activity is also framed as a key consideration particularly while home working – similarly to findings in Chapter 5. The above findings confirm past findings -see Chapter 4 (office space) and Chapter 5 (domestic workplace) and validate the design directions that have been framed in these two past Chapters, which will be further discussed in the subsections below.

6.4.2. Novel directions for Biophilic & Biomimetic design in the (hybrid) workplace (RQ2)

Co-design workshop (W02) highlighted the need for enhancing nature in the built environment; illustrated in all participants' scenarios where plantings were present. Plants and nature were viewed from participants as contributing to wellbeing in many levels; as participants connected them to different aspects of wellbeing utilizing diverse feedback systems **(RQ2)**. In P8's scenario as an element to enhance environmental, physical and emotional wellbeing; providing an activating effect through visual and olfactory feedback when too little physical activity is detected. In P08 & P09's group scenario nature is also linked to social wellbeing, where nature as projection provides an opportunity for social connectedness. In their scenario, nature is brought in as a projection on building's surfaces; activated when too little physical activity is present. In P10's scenario, plants are mentioned in the context of improving air quality and environmental wellbeing; P11 & P10 mention nature in the context of environmental wellbeing in their group scenario. In P03's scenario, and in P03&P12 group scenario, plants are linked with social wellbeing and physical nourishment; providing a space – both physical and virtual- to interact with others while caring for them. P03 & P12 rethink the human-nature relationship in an active manner; plants are not placed in the periphery but are key in instrumenting social relationships in the workplace, creating communities of people that care for them – even remotely.

Bringing nature in the built environment has been the prime concerns of biomimicry and biophilia in design [91,180,213,286,424]; with biomimicry being primary the study of transfer of natural processes into the artificial world, whereas biophilia the study of the interaction between humans and nature [180]. The above scenarios strongly point out novel directions for biophilic design in the context of workplace wellbeing **(RQ2)**. Beyond the obvious request of bringing more plants in the office, the analysis of the scenarios unpacks what nature symbolizes in terms of wellbeing dimensions for the participants, providing new insights on how biophilic design can support these dimensions. For the participant's, nature appears to be restoring but also alerting; directly linked with emotional wellbeing; it prompts towards increasing physical activity – moving more in the workplace or outside - and provides a venue for social interactions to take place – either in the context of creating more appealing environments, or for the purpose of creating communities that nurture care for nature; linking nature with social wellbeing and human to human interaction. With regards to biomimicry, the scenarios illustrate novel sensing and feedback mechanisms - such as utilizing nature as projection or the sensory enrichment of plants - which can inspire towards developing feedback interventions **(RQ2)**. These are further analyzed below.

The visual analysis of the scenarios involving nature unpacks novel directions for biophilic design and physical feedback in that context, to support human-data relationships for wellbeing. In all scenarios plants appeared to be instrumented; utilizing environmental sensors to monitor their needs and provide feedback to the building occupants to care for them collectively – this extending to using IoT to connect to a virtual plant "self" to engage hybrid workers in P03&P12 scenario **(RQ2)**. Participants mostly refer to the green color as the key positive aspect of bringing nature in the workplace; and indirectly on improvements in microclimate - using phrases such as 'calm', 'pleasant', 'activating' to describe such spaces (see P03, P08, P10's scenarios). Beyond plantings, participants discussed projections of greenery on doors and windows, turning architectural elements into calming displays; which provides interesting avenues for further exploring materiality, light and projection in the context of biophilic design and data awareness **(RQ2)**. Participants indirectly referred to air quality improvement as a key consideration behind bringing nature in the office – including air flow (see P08's, P10's and P11's scenarios). P08 takes that further into discussing ambient feedback using plantings; mentioning leaves and plants movement, air flow and smell as feedback for physical activity, thinking nature's instrumentation in the context of actuation and not only sensing **(RQ2)**. P08's scenario points towards considering air flow, air circulation and humidity –when referring to 'freshness'- as part of air quality improvement and environmental wellbeing; and points towards novel directions for feedback. These involves visual feedback – e.g. shape changing actuation of elements that are either natural or imitating nature - pneumatic actuation – utilizing air to foster actuation- and olfactory feedback – utilizing the sense of smell for awareness purposes **(RQ2)**.

The co-design activities provided cues for novel physical data interactions for biophilic and biomimetic design; establishing design directions for physicalizing data and enhancing data awareness - as illustrated in the findings described previous subsection and in Chapters 4 and 5 **(RQ2)**. The above findings provide novel directions for biomimetic feedback that can be used in the context of social wellbeing, but also physical and environmental wellbeing – including air quality awareness, a key finding from Chapter 5 - and point towards the further exploration of biomimetic, actuating, shape and color changing feedback for that purpose **(RQ2)**. Biomimetic feedback can foster biophilia in the buildings for work, supporting the nurturing of embodied awareness (emotional and physical awareness); as an element to design restorative spaces and calming feedback and as a technology to enhance social interactions **(RQ2)**.

Focusing on climatic aspects – as a response to quotes on air quality- slow and passive environmental responses driven by biomimetic mechanisms such as pneumatic elements [131,408] could provide indications of air quality aspects and breathing patterns, encouraging a more 'embodied' approach to experiencing and acting on the micro-climate[221]. Utilizing soft sensors and actuators, passive data processing and the diversity of smart materials and meta materials, all broadly linked with Soft Robotics agenda [36,328,408]; biomimetic feedback can be used in passive technologies for user-control of domestic micro-climate [49,71]. Thermochromics applied on desk-used objects or window blinders or curtains for instance [240,244]; can be used as a passive and calm display to illustrate deteriorating air quality without dominating attention or requiring a constant checking of one's smartphone or screen. A relevant project that explored interior elements as air quality displays is Shutters [71]; illustrating potentials of room dividers to act as physical displays for air quality data, utilizing the use of SMA wires. Such mechanisms can be further explored in the context of air quality awareness in the shared and domestic workplace.

6.4.3. Data for wellbeing: data sharing perspectives **(RQ2)**

The two workshops have provided broader insights on data collection and data-driven feedback for wellbeing in the shared and remote workplace. Participants views on data collection in the built environments suggest the following:

a) the prioritization of environmental data – see scenarios by P08, P09, P03, P10, P11 where air quality, humidity and temperature are mentioned in the context of enhancing environmental wellbeing and foster plant growth in the buildings; also mentioned in context of air quality awareness by P01, and broader wellbeing considerations by P05, P06.

b) use of occupancy data, in scenarios that address social wellbeing complementary to biophilia (P08, P09, P03, P11); broadly seen as privacy friendly data;

c) use of movement and physical activity data (P08, P09, P10) with caution. Such data carry double connotation; many participants' scenarios pointing towards the use of such data to promote physical activity in the workplace, on the other hand, results from workshop 01 suggest that sharing such data should be done with caution and using it publicly is not favored (P05, P06);

d) use of physiological data collected through wearables is mentioned in some scenarios as a way to assess emotional wellbeing (P08, P10, P12); though privacy concerns emphasize on personal use only – or in aggregated manner (P10&P11);

e) prioritization of active data collection with regards to assessing emotional wellbeing. Participants in Workshop 01 (P05, P06) suggested that the combination of environmental & occupancy data with self-reported emotional wellbeing data can provide important insights for wellbeing in the buildings for work. For the latter, they recommended active data collection – i.e. requiring conscious participant engagement and consent.

Apart from data collection and privacy considerations, co-design highlighted views on data sharing in the workplace. P10 & P11 group scenario viewed aggregated data sharing as a way to support wellbeing awareness in the workplace. In their group scenario, they suggest that the visual representation of key environmental, physiological and physical data in the workplace can provide avenues to the building occupants to assess their wellbeing. Such interventions have difficulties in materialization with regards to privacy– i.e. assessing group emotional wellbeing from physiological sensors has its privacy challenges [99,193,420]; but the underlying idea of surfacing aggregated data together for awareness purposes and to foster building occupants' own interpretation of wellbeing can be a meaningful direction. Moreover, what is indirectly suggested in the ability to have data accessibility and awareness and the ability to make associations between environmental data and indoor climate, and physiological and physical data and associated wellbeing – i.e. physical activity, fatigue and mood. Linking embodied experiences of one's wellbeing and environmental aspects through data representations can foster group awareness and deeper understanding of how these two aspects correlate. These findings have been previously unpacked in Chapter 5, suggesting design directions on ambient feedback for awareness, and have now been revisited here through the co-design sessions.

Most of the participants across workshops referred to data to support and not replace human decision-making [215,343]; envisioning scenarios whereby data provide awareness to the building occupants about different aspects of wellbeing so that they can act themselves. Some scenarios illustrate tensions between AI-driven space that automatically restore wellbeing (see P10, P12); and user-driven spaces where data is used for awareness purposes only (see P03, P08, P09); with the broader consensus leaning towards data for user-driven workspaces. These findings confirm previous relevant findings in Chapter 4.

6.4.4. Chapter 4,5,6 Findings Summary and next steps towards Design Interventions (RQ1, RQ2)

Re-framing the initial objectives of this chapter, it is to validate previous empirical observations as per Chapter 4 & 5 and solidify design directions as per Chapter 4 & 5. This is accomplished through two qualitative studies engaging the building occupants, a focus group addressing wellbeing in the hybrid workplace; and a co-design session using a custom card-deck that addresses aspects of wellbeing, sensors, spaces and physical affordances. Together with the findings of the previous Chapters, this Chapter contributes to discourses around Human Building Interaction (HBI) [142,143,209] research with findings led to a framing of a physical design agenda to support the wellbeing of the shared and domestic workplace.

The findings of this chapter repeat past observations, providing credibility on key past findings and design considerations. Key findings and key aspects of this design agenda are:

a) the lack of control over one's surroundings has negative implications to wellbeing; pointing towards DIY and user-controlled interfaces for customizing the workplace's physical and environmental dimensions and negotiating boundaries.

b) multiple mentions of air quality as a multidimensional issue – e.g. air flow, temperature and humidity impacting perception of air quality –which further points towards designing and configuring solutions for the domestic and shared workplace.

c) perceived inaccessibility and underutilization of data collected by the building; emphasizing on data awareness technology to make this data useable by its occupants, allowing levels of control with regards to data sharing.

Moreover, this chapter revisited design implications as stated in the previous two chapters, and extended the discussion on the design of potential interventions framed under biomimetic and biophilic design. New finding concerns biomimetic design and novel aspects of actuations involving (or imitating) living organisms; spanning on physical and visual feedback, ambient movement, and olfactory feedback. Beyond restorative spaces and environmental wellbeing, biophilia is highly associated with social wellbeing and collaborative aspects; which prompts towards considering collaborative dimensions when designing for feedback for wellbeing in the buildings. Finally, data collection considerations highlight minor privacy concerns over the use of environmental and occupancy data, frame the use of physical activity and motion data with caution; and prioritize active data collection with regards to emotional wellbeing.

Moving forward, key design considerations for feedback systems to support wellbeing include:

d) Emphasis on physical and tangible design dimensions of awareness technology; with the purpose of bringing latent environmental aspects into the experience such as air quality.

e) Exploring collective and collaborative – i.e. embracing user control - and active – i.e. fostering physical activity and movement in the workplace - dimensions of biophilic design; framed under a physical design agenda.

f) In the context of supporting biophilia; further engaging with biomimicry as a design principle and source of inspiration. This extends to the choice of materials and sensing-actuating mechanisms to produce feedback; as well as the use of nature-inspired metaphors to communicate information.

Moving forward into Section C, this PhD project will explore the potential of the above design agenda through prototyping and evaluating an intervention as a response to key findings. Doing so, I re-visit below the concept of a design intervention which I suggested in Chapter 5, with the prospect of materializing it in Section C; re-appropriating it to respond to some of the above considerations. It is important to highlight that this intervention does not aim to respond to all findings and design considerations; but addresses some key selected findings and follows some key design considerations. With this PhD work being generative in nature; each chapter provides its own contributions while opening new opportunities for further research. Following this approach, Section C responds to key findings while framing new opportunities and challenges for design research on physical displays in the context of wellbeing in the workplace.

6.4.5 Responding to key findings: Concept for ActuAir display for air quality (AQ) awareness

ActuAir is a physical intervention that responds to air quality data; in the context of providing awareness on climate and supporting environmental wellbeing in the workplace. ActuAir was conceived as a response to key findings around perceptions of control (Chapter 4, 6) and air quality (Chapter 5, 6); and is further pursued in Chapter 7 as a potential intervention for materializing and evaluating design directions described in Chapters 4,5 and 6.

Findings in Chapter 5 and 6 point to 'surfacing' air quality data in the buildings to increase building occupants' awareness of climate can be a meaningful way to support decisions that can enhance environmental and emotional wellbeing. There are many aspects of air quality experience and management unaddressed by current research on the workplace [83,187,343,422]; much of the research on air quality is limited to CO2, leaving the experience of humidity, temperature and air flow aside. Design research can focus on developing ambient and physical feedback that surfaces different aspects of air quality; both addressing users' embodied experiences and creating meaningful experiences based on sensory readings. Physical representations of air quality feedback that are closer to the embodied experience of aspects of air quality could deepen awareness of one's body and environment, and how these two aspects relate to each other.

Based on this idea, the above findings on biophilic and biomimetic design can guide the development of human-building-interactions for air quality awareness in the shared and domestic workplace. To do so, in the following Chapters I engage with the emerging Soft Robotics and Actuating Materials agenda [36,328] as it primarily brings biomimetic and biophilic design mechanisms into HCI research [128,272,276,371]. Examples of Soft Robotics applications are pneumatic systems [131,328,400,419], Smart Memory Alloy polymers [240,246] and Thermochromic systems [319,346]. The application of such mechanisms for air quality awareness should address broader findings on aspects of control, data accessibility and useability, and scale of interventions in the buildings (Chapters 4 & 6); meaning that the intervention should be customizable from the building occupants both in the physical – e.g. translated to modularity and portability – and digital – e.g. ability to control data sources – dimensions. Similarly, responding to relevant findings on privacy (Chapter 4 & 6); environmental data is primarily considered, with a view to potentially integrate occupancy data.

More specifically, speculating on the design of ActuAir air quality display; modular pneumatic elements responding to air quality data can compose shape changing room dividers, desk barriers and window covers, creating different types of workplace surfaces and enclosures, and visual barriers with display capacity. Such Inflating and deflating elements inspired by breathing mechanisms could support a more embodied awareness of micro-climate while providing a visually aesthetic experience. Another mechanism with potential interest is the use of Smart Memory Allow (SMA) wires and polymers in combination with textiles – see Shutters [71] for instance- used to imitate movement of trees' leaves based on air quality data streams, inspired by relevant findings in the co-design section. The complementary use of thermochromics to further communicate material color feedback is further considered. These mechanisms will be explored in depth in the next Chapter, which is dedicated to the design and material exploration of soft robotics for the purposes of physicalizing air quality and climatic data in the buildings for work.

6.5. Limitations

This work has a number of limitations with regards the selection of participants and the limited amount of co-design sessions; resulting in limited data sample. Additionally, the custom card kit should be evaluated with experts (e.g. architects, interior designers, furniture designers, environmental consultants) through expert design criteria workshops to support future studies.

6.6. Conclusions

This work addresses the wellbeing experiences of building occupants while working from home during a period of hybrid working, and provides insights on their views on data collection and use for wellbeing purposes in the shared and domestic workplace. Through a focus group and a co-design activity, the studies highlight key findings such as the importance of the perception of control for wellbeing; the importance of enhancing utilization and awareness of data or wellbeing; and novel dimensions for biophilic and biomimetic design. Contributing to discourses on Human Building Interaction (HBI) [142,143,209] research, these findings led to a framing of a physical design agenda to support the wellbeing in the shared and domestic workplace; designing ambient and physical feedback that supports embodied and environmental awareness through passive sensing. The proposed agenda is composed under the premise of co-creating smart environments together with their occupants and not for their occupants; this is useful to guide future interventions in the context of hybrid workplaces and highlights areas of critical research interest for Human-Building-Interaction and Soft Robotics [36,328] in the Built Environment. Future work will expand on responding to key findings and materializing this design agenda, developing working prototypes around the concept of ActuAir air quality display, and evaluate the experience of these interventions with the building occupants.

6.7. What is Next?

The next Section is dedicated to design research; responding to some of the above key findings through designing, developing and evaluating a relevant intervention – i.e. ActuAir as described above. Chapter 7 is primarily design and material exploration as a response to the above findings; Chapter 8 concerns the installation and evaluation of a final prototype in the workplace with the purpose of evaluating it with the building occupants.

SECTION C. UNDERSTANDING MATERIALITY. DESIGN AND MATERIAL EXPLORATIONS

DESIGN RESEARCH AND EMPIRICAL FINDINGS

Chapter 7. Design Research on physical displays for air quality data awareness: Making ActuAir

7.1. Introduction

7.1.1. Research Context

Smart buildings become increasingly more sensory-rich and data-driven, promising better energy management and health and wellbeing benefits for their occupants. Findings from my studies on the experiences of the building occupants of a quantified workplace building (USB, UK) (see Chapters 4, 5) highlighted the need for interfacing such data to the occupants. My findings highlighted that data physicalizations in the buildings can provide opportunities for them to become aware, experience, access and use this data for their own wellbeing (see Chapters 4, 6). The material and physical design agenda for data feedback in the buildings – particularly research in novel materials and aspects of scale (physical and temporal) of data representations and interactions in the buildings - remains relatively underexplored, providing great scope for design exploration (see Chapters 4, 6). Additional findings from the studies on the domestic as well as the hybrid workplace unpacked dimensions of wellbeing (using categories as identified in PROWELL model of workplace wellbeing assessment) and data relationships in these contexts; highlighting pressing concerns on environmental wellbeing - air quality as a latent but important aspect amongst them (see Chapters 5, 6). Biophilia and biomimicry as design themes came across when co-designing for wellbeing in the hybrid workplace (see Chapter 6), pointing towards further engaging with relevant literature for the purpose of conducting design research on the matter.

As a response to the above findings, in this chapter I report on my exploration of the design space of physicalizing, materializing and surfacing environmental data following a design research approach. Responding to key findings related with biophilic & biomimetic design, I have focused on exploring related work that brings physical and material design research and biomimicry together; such as the emerging soft robotics and actuated materials agenda [36,328,371]. Key in this design agenda is the development of non-rigid programmable materials to materials heavily inspired by natural mechanisms and processes, to materialize movement, shape change and color change, and more [328,408].

This work gets inspiration and builds upon relevant design research on the making of soft Robotics and actuated materials [36,328,371] , their application in interactive and adaptive architecture – see the work of Tobias Becker's Breathing Skins[139] Project on pneumatic facades (Figure 59); Doris Sung's work on Thermobimetal skins [358]; or Lumina by Khoo et al. [184] – as well as on interior design and customizable and shape-changing furniture – see LiftTiles by Suzuki et al.[360]; Sarah Nabil's textile Smart Memory Alloy (SMA) artifacts [240]

[139] https://www.tebe.berlin/innovation/realisation/

(Figure 58); Jie Qi's textile origami robotics[140] [304] (Figure 60) ; and Shutters by Coelho and Maes [71]. The specific literature and the online tutorials which were used throughout the making of the artifacts is briefly discussed in the next section (also in the background chapter) to help further contextualize the design work that follows.

Figure 61: On the left, the work of Sara Nabil "Seamless Seams"**[245]** combining SMA wires with bacterial color-change showcased in an exhibition; on the right, 'Shutters' **[71]**, a room divider/air quality display enabled by SMA wires.**62**

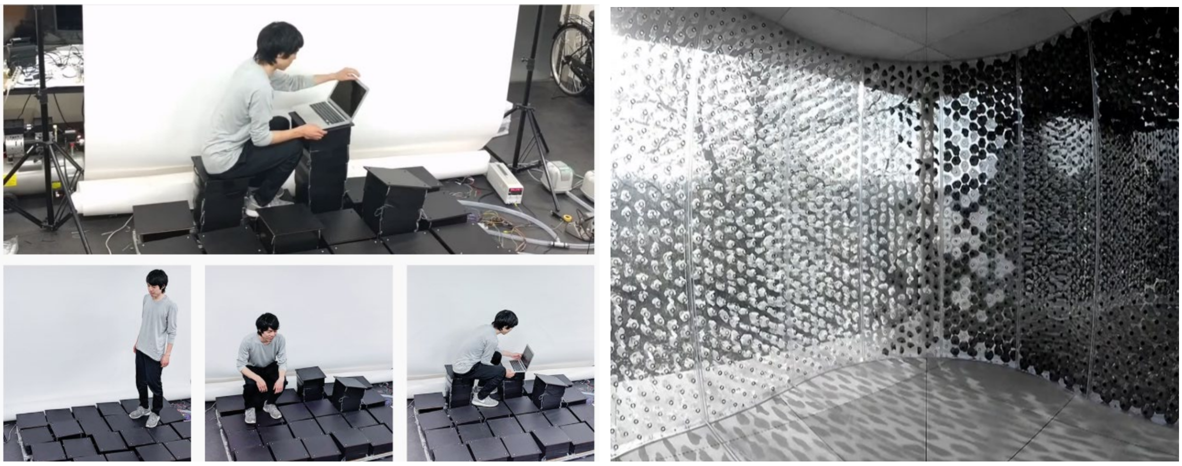

Figure 63: On the left, LiftTiles**[360]**, employing pneumatic actuators to create adaptive interiors. On the right, Breathing Skins by Tobias Becker, using pneumatic actuators in a façade to create in-and-out air flow. 64

Drawing upon such relevant research, this chapter explores the potentials of shape and color changing materials through the making of actuated artifacts with the purpose of providing air quality awareness. These artifacts are further connected with specific environmental data sources, to provide climatic data feedback in the workplace.

There are different factors driving the design exploration described in this chapter; which derive from the findings of the previous chapters. One key factor derives from the discussions around physicalizing and materializing data framed withing biomimetic design as mentioned above; which drove the design interest around the soft robotics and actuated materials agenda

[140] Also see https://www.exploratorium.edu/tinkering/tinkerers/jie-qi and http://technolojie.com/

as heavily influenced by biomimicry [128,371]. To start my design exploration, I drew on soft robotics & actuated materials design research to map design works relevant with the architectural scale; to create a basic understanding on design patterns and materials heavily used in architectural interiors and building construction. Moreover, I further explored biomimicry as design inspiration for environmental feedback; drawing upon understanding shape and color change as feedback in natural organisms, and how this translates into building interactive architectural elements.

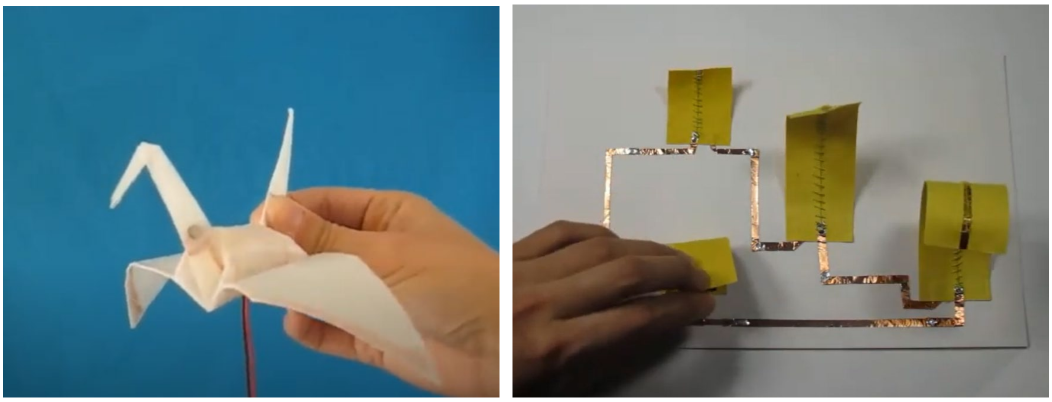

Figure 65: Jie Qi's work on interactive origami structures and soft robotics.

The second key factor that drove design exploration was based on the findings around user control and customizability; which was translated to designing prototypes that provide data awareness through physical feedback, but also allow customizability of this feedback by the building occupants. This design approach aims to address the often-prevalent gap between Design Research and Co-Creation practices in HCI through introducing customizability of the physical artifacts used as research prototypes; allowing users to actively interact with the data and co-shape the ways the artifacts surface information and their physical positioning in space, and as an extension, the spaces they inhabit. Physical scale – addressed through modularity - and temporal scale of feedback – feedback speed and repetition - were dimensions that I chose to be customizable by design; treating both as research variables in studying how data is experienced by the building occupants.

7.1.2. Research Questions

The research question this chapter responds to is

RQ3: What design interventions can support data experience[141] for wellbeing in the quantified buildings for work?

RQ3a: What feedback design can support wellbeing through experiencing data in the buildings?

[141] Data experience: experience of data in-place

Responding to this question, this chapter describes the thought process, the design and making of customizable shape and color changing interactive artifacts to display air quality data at scale at the buildings for work. Doing so, it is structured in 4 sub-sections; presenting work in progress in a chronological order. Sub-section 7.4.2 concerns the initial design research including concept design and 2D & 3D design work on artifacts. 7.4.2 starts with a brief mapping of shape & color change forms and patterns in architectural and interior design; it then describes the 2D & 3D design process of artifacts; accompanied with the decisions around further pursuing specific color & shape change patterns. It ends with the development of animated 3D examples of the future artifacts; used as validation tool for progressing to the next stage of physical prototyping. In Sub-section 7.4.2. I report on experimentations on the physical prototyping; the process of making a series of color and shape changing artifacts, illustrating the failed and successful design experiments on form-finding, and material combinations; accompanied with the development of different hardware to control it. As illustrated in 7.4.2. I explored two distinct actuation systems: folding/unfolding using felt fabric and SMA wires, and inflation/deflation using silicone rubber and air pumps; and color change using thermochromics across both systems. After experimentation, I chose which of these two systems is more promising and for further exploration. In sub-section 7.4.3. I report on further material research on pneumatic actuation mechanisms, the attempts to combine color change with inflation and the introduction of LEDs to overcome problems. Sub-section 7.4.4. describes the making of the final prototype together with the hardware and software to control it. The section 7.5. is the discussion, concluding with a summary of the key takeaways referring to the knowledge obtained through making, the successes and failures, and avenues for further research in the area of actuating materials as air quality displays; as the main contribution points of each of this chapter.

7.1.3. Research Contributions

This work is framed within Human-Building Interaction-research field, addressing climate-responsive, biomimetic and biophilic design in adaptive architecture [213,358]. Responding to previous findings relevant with promoting air quality awareness and enhancing control through data materializations; this chapter explores the making of physical representations of environmental data at scale in the buildings, addressing the lack of situated data-experiences for supporting the occupants' environmental wellbeing.

The purpose of this chapter is to illustrate the design and thought process, the challenges behind, and the knowledge obtained through the making of large scale, customizable, shape and color changing artifacts. Documenting the process of engaging with shape and color changing materials, the challenges of combining them, the derived avenues for further exploration, the hardware and software accompanying the final prototype can be of value for designers & researchers working in similar areas. This is the core contribution of this chapter; to provide a 'how-to' guide for building soft robotic artifacts for interfacing environmental data in the buildings addressing challenges in the making process and opportunities for future work.

7.2. Methods

Following a Design Research methodology [129,425], I report and document in this chapter the thought and design process of making a large-scale customizable air quality (AQ) display enabled by soft robotics. Doing so, I created a 'Portfolio' of work as a documentation of my design and material explorations spanning across the following section; heavily utilizing images and short videos [30] to support all my steps and hands-on knowledge obtained. This approach of presenting design work is considered appropriate for design research – see Pierce [297] and others [80,307,382]. The next section (section 7.4.) consists of 4 sub-sections which illustrate 4 steps in the design research process; with each of them contributing with design findings around the learnings of working with specific materials and the key insights on failures and successes of relevant experiments; framed as "Opportunities and Challenges".

The next 4 sub-sections of this chapter are dedicated to the reporting on design activities, presenting work in progress in a chronological order through text and images. Sub-section 7.4.1 concerns the initial design research including concept design and 2D & 3D design work on artifacts. 7.4.1 starts with a brief mapping of shape & color change forms and patterns in architectural and interior design; it then describes the 2D & 3D design process of artifacts; accompanied with the decisions around further pursuing specific color & shape change patterns. It ends with the development of animated 3D examples of the future artifacts; used as validation tool for progressing to the next stage of physical prototyping. Sub-section 7.4.2. I report on experimentations on the physical prototyping; the process of making a series of color and shape changing artifacts, illustrating the failed and successful design experiments on form-finding, and material combinations; accompanied with the development of different hardware to control it. As illustrated in 7.4.2. I explored two distinct actuation systems: folding/unfolding using felt fabric and SMA wires, and inflation/deflation using silicone rubber and air pumps; and color change using thermochromics across both systems. After experimentation, I chose which of these two systems is more promising and for further exploration. In sub-section 7.4.3. I report on further material research on pneumatic actuation mechanisms, the attempts to combine color change with inflation and the introduction of LEDs to overcome problems. Section 7.4.4. describes the making of the final prototype together with the hardware and software to control it. Section 7.5. summarizes key learnings from all these sections around working with different materials, and points towards directions for future design research on actuating displays for air quality.

7.3. Activities & Observations

7.3.1. Initial Design Research (October 2021-November 2021)

Initial Design Research subsection includes the following:

7.3.1.1. Mapping design patterns and materials.

7.3.1.2. Room Dividers as Displays: Rethinking Shutters.

7.3.1.3. Early material exploration and 3D experiments.

7.3.1.4. 3D and Animated Visualizations.

7.3.1.1. Mapping design patterns and materials for shape changing interior architecture (October 2021)

Based on the above relevant background literature on soft robotics and biomimicry [371] and their application on architecture and interiors, and with the purpose to guide my early design stages, I created the below material & shape change typologies (see Figure 61). These high-level typologies concentrate some of the core shape and color change mechanisms observed in natural organisms as interpreted by past shape- changing architecture and interior architecture projects. The categories address the shape change effect, form factors and materials used to achieve it; creating equivalences between materials & shape change patterns seen in climatic skins with fabrics and inflatables used in interiors. Some of these design typologies include expanding and contracting of cushion-like elements - see pneumatic facades in architecture [131] or vinyl inflatable artifacts [400] ; rotation of semi-rigid elements using soft-robots - see passive facades [358] or paper-based prototypes using SMA wires [304]; bending and unfolding of material surfaces – see works utilizing thermobimetals, hygromorphic, composite materials [402] etc. - and diverse origami-like and auxetic patterns [407] utilizing composite materials and fabrics in different scale and materiality in the built environment. These typologies served as a high-level classification of form factors and materials as found in past shape changing architecture and interior design projects, to guide my upcoming design of prototypes and early material explorations.

In terms of materials; based on background literature, materials often include fabrics and soft polymers such as silicone rubber, and combinations of these materials. Such materials are commonly used in interior installations/design, wearable design and tangible applications; are easy to use and integrate in prototyping in different scales in the buildings.

Based on past projects, I chose the following materials for experimentation:

- Felt fabric; textured fabrics (see image below)
- Conductive fabric, thread, ink (Bare conductive)
- SMA wires (Nitinol .06 HT and 0.01 LT)
- Thermochromic pigments (SFXS)
- Silicone rubber (Eco-flex 0030)

The combination of the above materials results in different interactive probes and prototypes, through an open-ended design exploration.

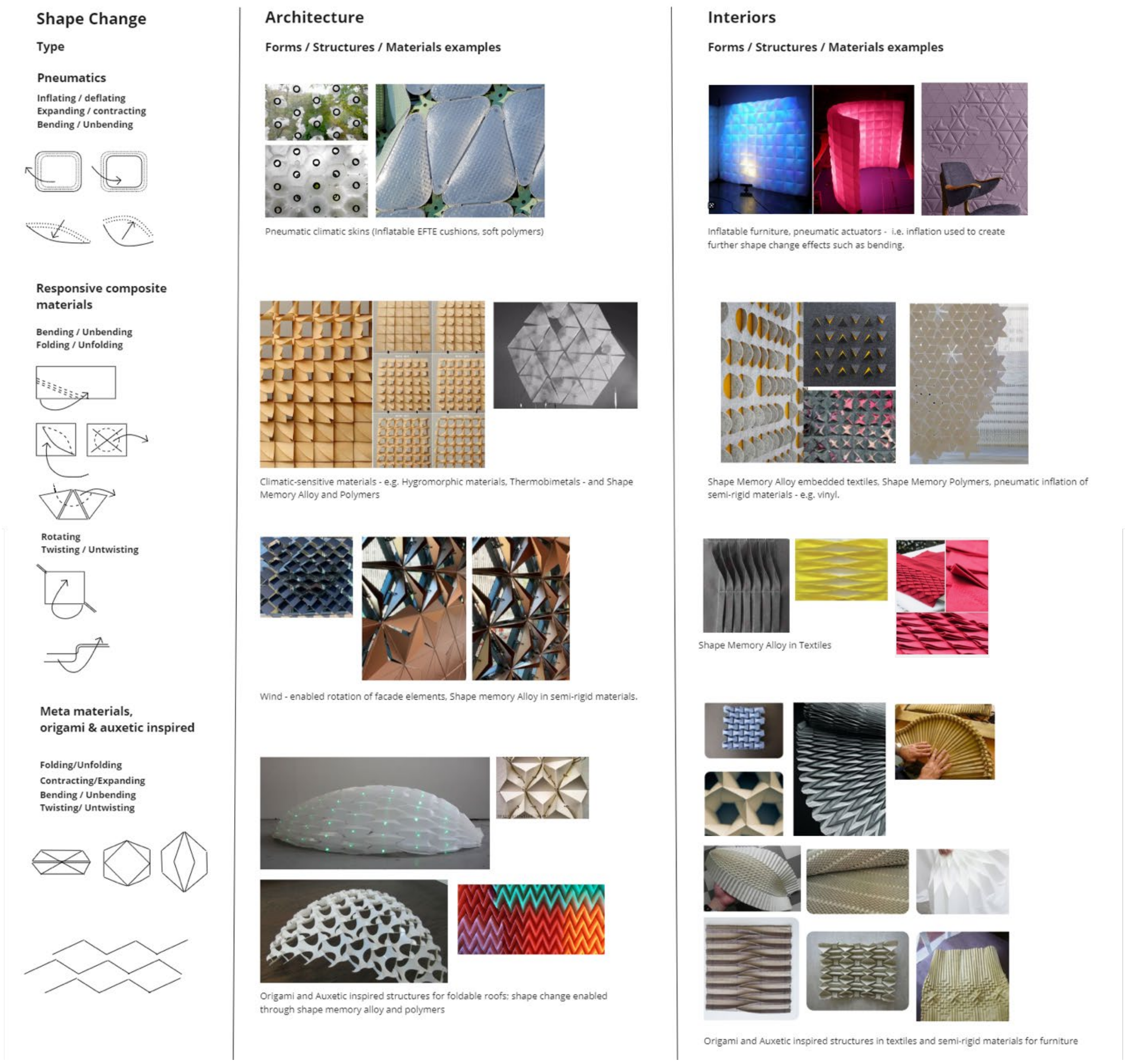

Figure 68: Application of soft robotics in Adaptive Architecture: High-level categorization of Design Patterns, Typologies and Materials

7.3.1.2. Room dividers as displays: Rethinking Shutters (October 2021)

The focused examples on air quality adaptation and air quality awareness are a few -see Shutters[71], FloriAria [104], AuxeticBreath [407] an auxetic façade design with shape memory polymer – with Shutters being a major influence for the upcoming work. Shutters uses soft robotics to create architectural elements as data displays, specifically room dividers. Room dividers are very common in open-plan offices, illustrating a flexible way to organize areas of working, provide privacy, create enclosures for focused work, and provide sound proofing. Soft wall partitions are also common in the domestic space to support competing and alternating uses in limited space and provide visual barriers. Given the increased popularity of room dividers in office and domestic workplace; the fact that it is an affordable, lightweight, portable and transferable solution to support diverse needs; and their potentials to provide ambient feedback installed in the periphery of working areas as well as forms of physical and tangible feedback; room-dividers provide an interesting design space for physicalizing air quality data. My idea was to provide a shape-changing modular installation that forms an interactive soft wall partition, that is shape-changing display that interacts based on environmental (air quality) data streams. The reasons for this choice are twofold; one, room dividers provide an interesting 'middle ground' between the scale of architecture and skins (architectural facades) and interior elements (interior walls), which serves as implementing and evaluating design patterns existing in both- i.e. testing shape change concepts, patterns and materials used in façades in interiors and vice versa. Second, the scale allows for multiple user interactions: a different positioning in space can create different dynamics in their use as ambient display and room element, and communicate feedback in diverse ways. Modularity and coordination of independent elements – a 'radical atoms' approach [166]- comes as an additional variable to explore in design of interventions; enhancing further the potentials of interventions to take place in different arrangements and scales in the buildings, and evaluating spatial aspects of feedback perception.

I settled on the design of interior room dividers for the workplace as the design space for physicalizing Air Quality data; further re-thinking Shutters under a new lens to support physical and tangible feedback, modularity, and physical and digital user-customizability. Shutters [71] is a project about room dividers that provide air quality feedback through shape change; using Smart Memory Alloy wires embedded in felt fabric [240]. The installations provide ambient feedback when positioned against the sunlight; with the movement of the fabric creating different notations which are 'projected' as the shadow falls. Reflecting on this project, Shutters encompasses some very interesting concepts, but has also many challenges: the reality with many office spaces is that light is purposely maintained in a uniform level (decreasing any potential of the shadow effect); and it is often only from a few desks near the windows where a light interaction would be visible. In terms of feedback and aesthetics; the project could be redesigned using more interesting shape-change patterns, or utilizing different types of material combinations to provide a more visible feedback regardless of natural light and shading. In terms of biomimicry and the reference to air quality representations, Shutters has little to offer. Finally, Shutters remains a strictly ambient display; any physical user interaction is more likely to prove damaging for the display, which is definitely a limitation to the current project.

Seeing these problems as opportunities to expand the design space of shape-changing room dividers; I started first by re-thinking the form factors, design patterns and actuation principles behind it; as well as considering combining different actuating materials as feedback systems – i.e. combining SMAs and thermochromics to elevate feedback. This should be done with precaution; combining shape change using Smart memory alloy wires and Color change using thermochromic pigments can become complicated as these two systems create very different optical effects. On the other hand, their combination can enhance feedback experience and create avenues for communicating different aspects of air quality- such as CO2 levels and air flow, or real-time and historical data, or different climatic data that impact the experience of air quality, such as CO2 and humidity combined.

To make some of my ideas concrete, I produced some illustrations (using Photoshop and Illustrator). The concept below resembles Shutters (Figure 62), only that it would use the SMA wires (detail shown in upper right image) to create rotational /twisting movement to a composite fabric, creating different – and hopefully more 'organic'- shape changing patterns. The amount and direction of the gaps would be equivalent to the CO2 data, creating a symbolism of CO2 levels (see image below). An extension of the above idea includes the complementary use of conductive fabric, heating pads and thermochromic pigments to create color variation based on humidity levels; whereby more orange would mean more humidity or the other way around. The combination of these two systems – the shape-memory and the thermochromic one – can work complementary to create diverse symbolism around the physicalization of climatic data.

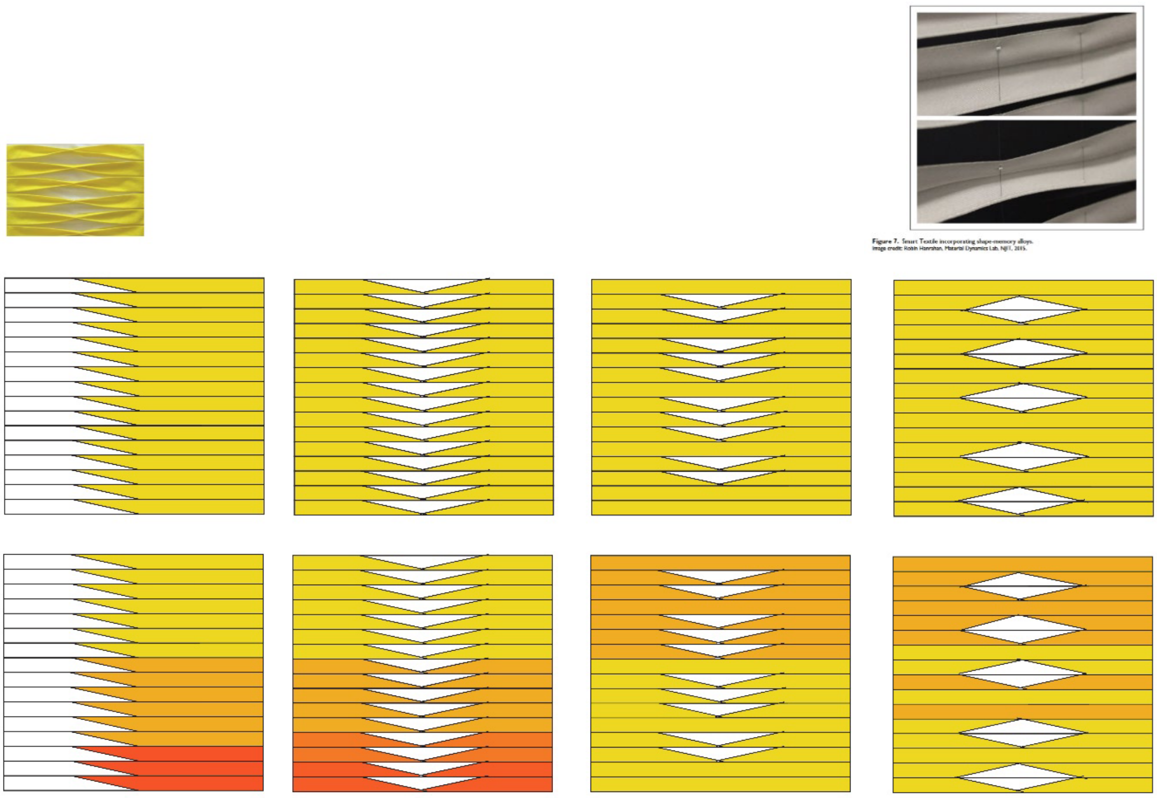

Figure 69: Rethinking Shutters- Combining SMAs & thermochromics

A variation of the above idea would be a room divider that physicalizes historical air quality data (time-series data) through thermo-chromatic pigments (Figure 63). The colors change based on the level of CO2; with each stripe representing an hour of entries. The current building's API provides environmental time-series data. Data is stored at a 24-hour basis; with each value updating in a dynamic way – i.e. whenever it changes. Custom software could normalize that, fetching data once every hour and keeping the middle value of the air quality data; based on this value, a hardware response generating heat (using heating pads or conductive metal/fabric) can manipulate the color of the pigment. Pigments have to be used in layers upon the fabric, starting with the most heat resistant – i.e. requiring more heat to become transparent – closer to the fabric's basis. The information about the temperature threshold of each color is obtained by SFXC[153] color pigments (Figure 64).

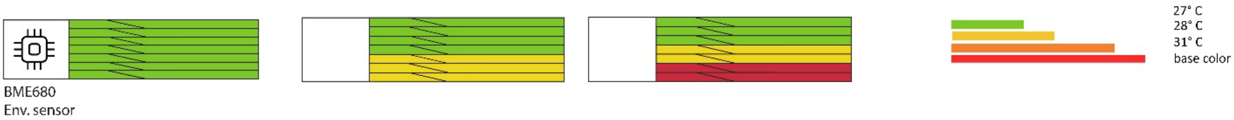

Figure 70: A concept of visualizing historic climatic data (24 hours of climatic timeseries) with layered thermochromic pigments (that have different temperature thresholds)

Figure 71: Thermochromic pigments and temperature thresholds**.**

Further considering thermochromic change on fabrics, fabric patterns and biomimicry to represent air quality; the color-change observed in leaves and leaf-patterns came into focus. Following the work of Aurelie Tu who engages with felt origami structures, the above principles of using thermochromics to create different artistic effects of CO2 data physicalizations were projected on her work. The images below illustrate how thermocromics can be applied on different organic felt fabric patterns; the cases below illustrate patterns that can be easily scaled to create room dividers or other objects (Figure 65). Here the colors transition from intense (when CO2 is low) to transparent (CO2 is high). It is difficult to create such color transitions; research on different types of conductive pads to generate heat might help resolving part of the problem.

[153] https://www.sfxc.co.uk/collections/thermochromatic-thermochromic-pigments-ink-paint

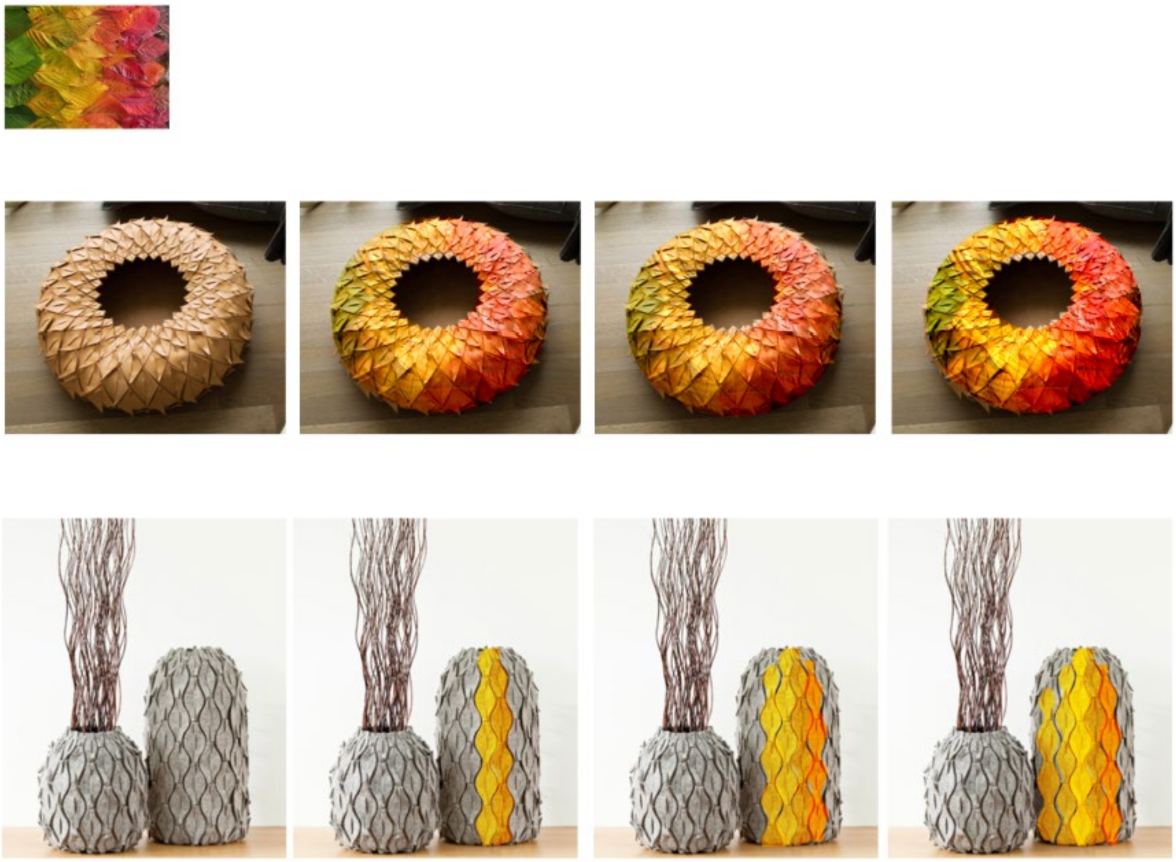

Figure 72: Thermochromic layers and organic (nature-imitating) patterns explorations

Another interesting design pattern evolves when combining many modular elements; each with a shape-change capacity. The concept below utilizes this idea creating a porous barrier; again considering the use of heat-responsive metals (shape memory alloy or thermobimetals) with a fabric. SMAs and thermobimetals change shape when heated. A latent aspect is that heated surfaces create differences in air circulation – enhancing the so-called stack effect. Basically the air around a heated surface gets heated and therefore lighter, resulting in moving up-wards; being replaced by colder heavier air etc. This effect can create air flow in interior spaces, which can enhance good air circulation or create problematic situations. Shape change can create awareness of a state change – such as CO2 levels -through dynamic openings/porosities; which can also assist or inhibit interior air circulation. The positioning of the surface can also play a role in that, while enabling users to customize their spaces creating interesting visual effects. Moreover, thermochromic change can raise awareness on pollution levels. Fabrics such as Spun Fiberglass can act as microparticulate filters. They can potentially enhance microparticulate accumulation, while the use of pigments on these fabrics can illustrate their real function. The image below illustrates some of these ideas of shape change (opening and closing of modules combined in a bigger surface) and color change (from neutral to color) based on data streams. The divider could be used in a variety of ways by the building occupants (as a divider, ceiling panel, or wall panel) (Figure 66).

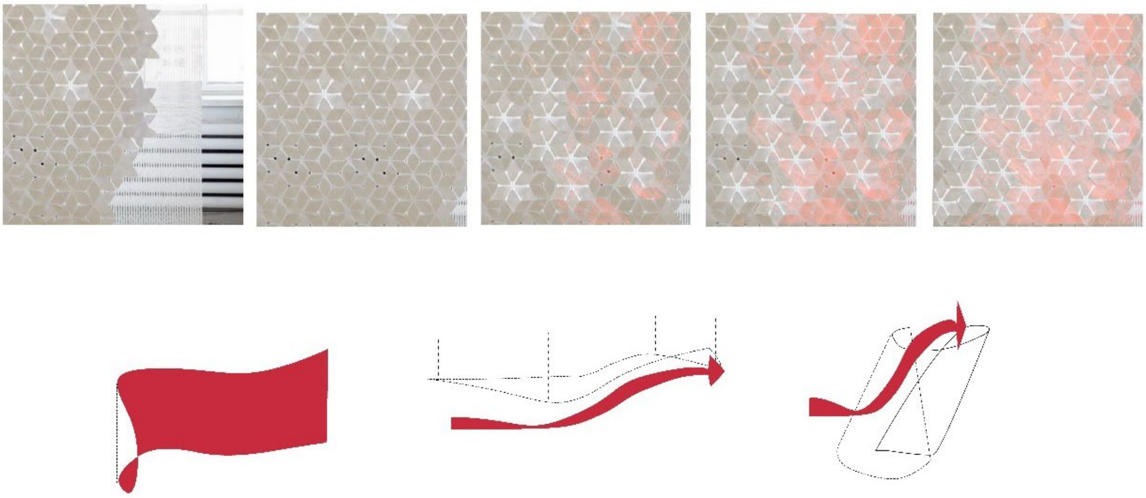

Figure 73: A visualization of an intervention concept to assist with air circulation through heated, shape changing and thermo-responsive elements

7.3.1.3. Early material exploration and 3D experiments (October 2021)

I had access to prefabricated felt components already installed as room dividers in the building. They currently function as room separators and sound barriers. They offered a solid basis to further develop soft actuations without having to create a divider from scratch, while supporting modularity and easy user-assembly. These components have an easy assembly system (plug in-out) to form greater surfaces.

Figure 74: The (preinstalled) prefabricated felt components used for developing my intervention.

My idea was to further 'dress' them with different materials that allow shape change. Initially, I consciously avoided to consider their form and configuration as a driving factor in design; as I wanted to explore the potentials of different patterns and material combinations. Later in the design & making progress, I started working with each module as a given. I started experimenting with felt fabric; imitating leaf-like design patterns (following the concepts above) and manipulating to experience how different sizes, patterns and shape changes can be perceived. Starting small, this approach helped me understand the material capabilities, and further consider how it can be used in combination with SMA wires and thermochromic pigments. These patterns would then be replicated on a greater scale and multiple times, creating room dividers. The images below illustrate the experimentation with folding, rolling and twisting – for now by hand, aiming to use SMA wires in the future - to create different leaf-like organic effects; some having more visual impact than the others.

Figure 75: Exploring the visual effect of textile shape changing patterns (aiming dress the prefabricated elements)

Following that activity, I developed some of the above design patterns in 2D&3D – aiming to both have a greater understanding of the visual effect of the replication of these patterns and shape-changing effects; and similarly create base-files to then be able 3D print and laser cut them using diverse materials. I used Rhinoceros 3D to develop these models; below some of these examples. These surfaces change shape following biomimetic concepts described above aiming to be used as wall additions or space dividers. 3D modelling is a very useful tool to experiment with shapes & patterns, shape change – i.e. how and how much can different surface patterns fold/curve/twist/flip and what is the visual effect – materials and lighting – i.e. using basic rendering to help understanding the future aesthetics - and the aesthetics of adaptation in animations – i.e. evolving variations of each pattern, as different models or model animation. Through this process, I have explored and understood the potentials of different patterns to create aesthetically pleasing representations, that can be then scaled to designing a room divider (or develop rationale for modifying the prefabricated one) (Figure 69).

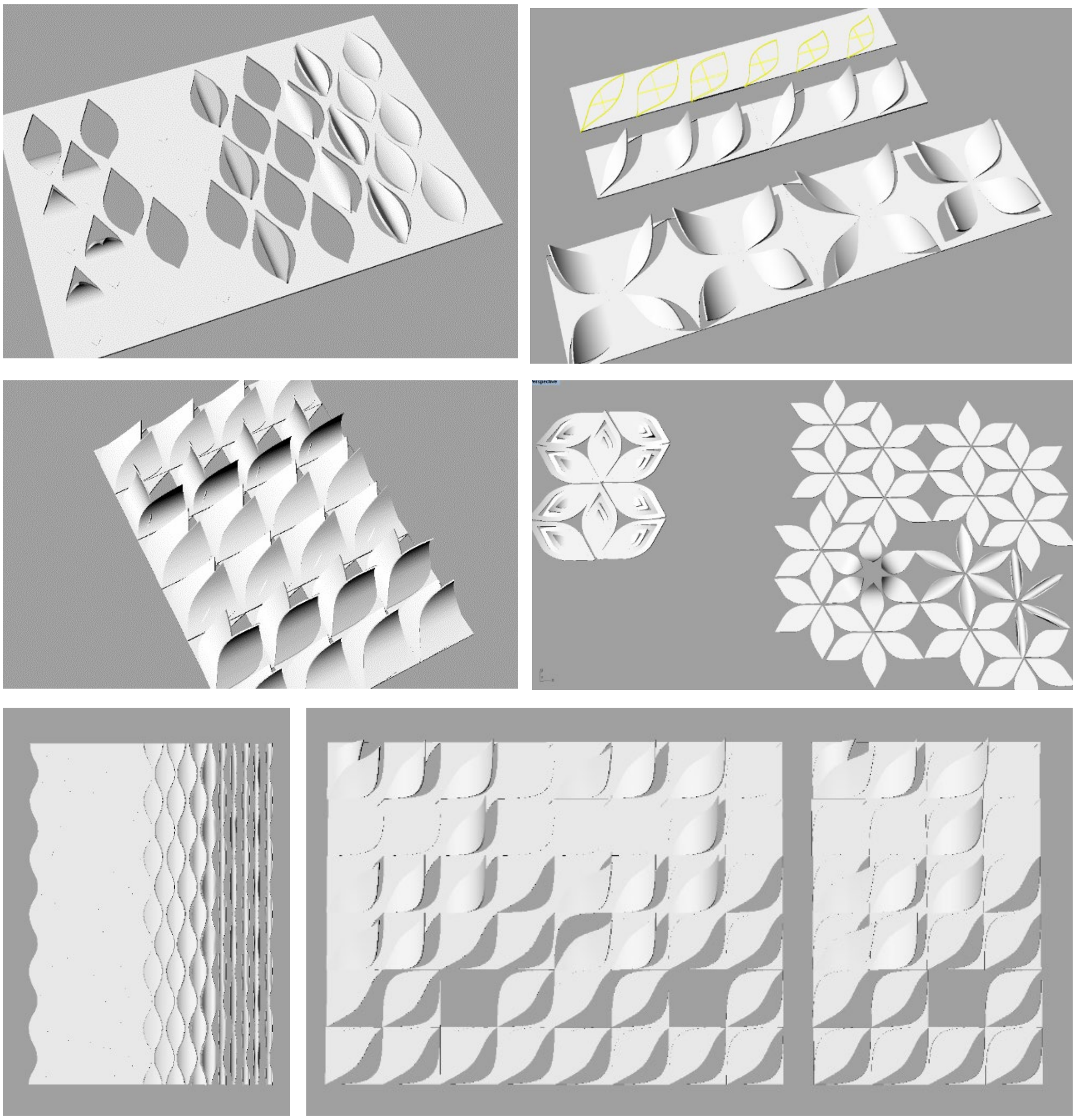

Figure 76: Transferring pattern explorations in 3D design experiments. Folding at y, x, z axis, rotating at y, x, z axis. Experimenting with volume and missing pieces (gaps), parametric shape change patterns using attractor points to create diverse optical effects.

The shape change is still not designed in an 'engineered' way; I had a rough idea how to place SMA wires but have not thoroughly designed it. Similarly, there was not a clear idea of the exact materials used; although I have chosen to start with fabrics and wires, the possibility of other material combinations was open. At this stage, form-finding was more important, and thinking around the feedback systems. In terms of feedback; I did not have a clear communication system in mind such as shutters. The alternation of voids and surfaces can create a 'shutters-like' communication system similar to the one of digital clocks; using this strategy to display letters or numbers (see example picture below). Voids and surface alternation can also create graphs lines, symbols such as arrows pointing towards directions etc. creating different types of symbolism. Lights and materiality can also play a big role in enhancing symbolism. I purposely kept design ideas at a more symbolic level for now; avoiding clearly deciding on a feedback mechanism and being mostly concerned about aesthetics created by the alternation of voids & surfaces.

7.3.1.4. 3D Visualizations and animations (November 2021)

Moving forward, I decided to focus on dressing the prefabricated modular room divider that I had access to; transferring many of the above shape-changing patterns to fit the size and shape of the existing modules. In 3D, I further experimented with shape-change variations as a form-finding exercise. I maintained the same principles of folding/unfolding leaf-like patterns – maintaining the idea of using bendable materials and SMA wires to dress the modules - testing the visual effect of shape change with 3D animations. Instead of using voids, I thought to create the visual contrast by using a different colored surface. This visual contrast can later be physicalized through material differences, or using different colors of fabric, or the use of pigments on fabrics.

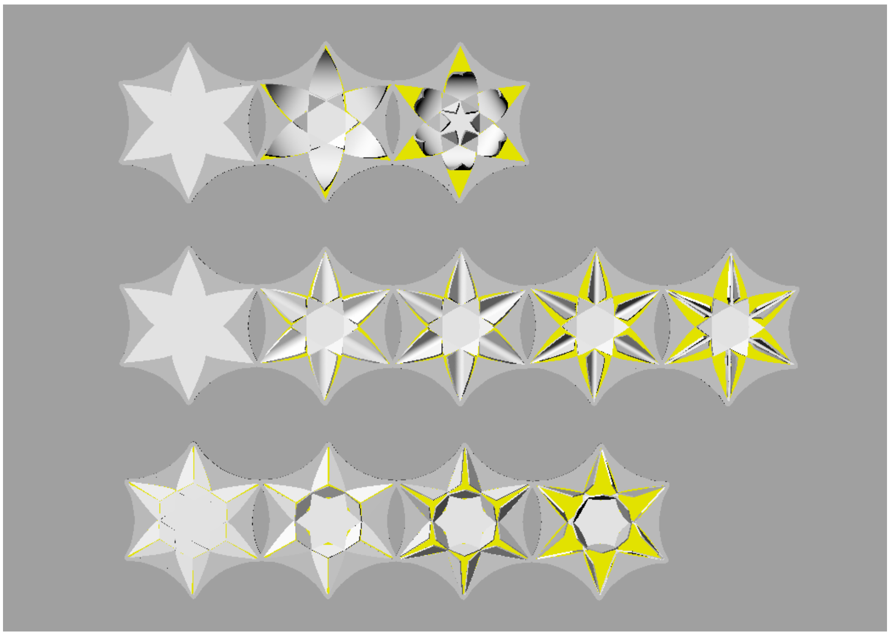

Figure 77: Design (3D) – of shape changing component with foldable parts (based on the prefabricated module).

I then combined these 3D animations into bigger constellations; experimenting with the potentials of shape change of clusters of modules. Apart from the visual effect of each individual module, the physical positioning and arrangement of many modules together, and the timing of the shape change – i.e. both the speed and duration of the shape change (slow/fast) as well as the moment of initiating the shape change – can create interesting visual effects. Actuating in groups, within different timeframes and in different arrangements, the modules can create different forms of feedback. Some attempts to visualize it can be seen below (see links for the animated versions[154]).

Figure 78: Animated simulations of shape change of the modular divider based on the pattern shown in Figure 70.

Beyond folding/unfolding, I started exploring the idea of inflation of components on the modules. Inflation and deflation seemed to match with the modules' materiality and design. Imagining them as expanding and contracting cushions, I created the following 3D models and animations. The same principles as above apply; different forms and patterns are tested, as well as different modular arrangements and temporal patterns of shape change. I considered inflation as a separate symbolic system, with inflation meaning a positive or negative change to a given state; focusing again on the representations aesthetics, and leaving space for different symbolic interpretations.

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[154] https://photos.app.goo.gl/1Asxs14pppWRrfXB6 and https://photos.app.goo.gl/Jqo3vXLPy9hxwm527

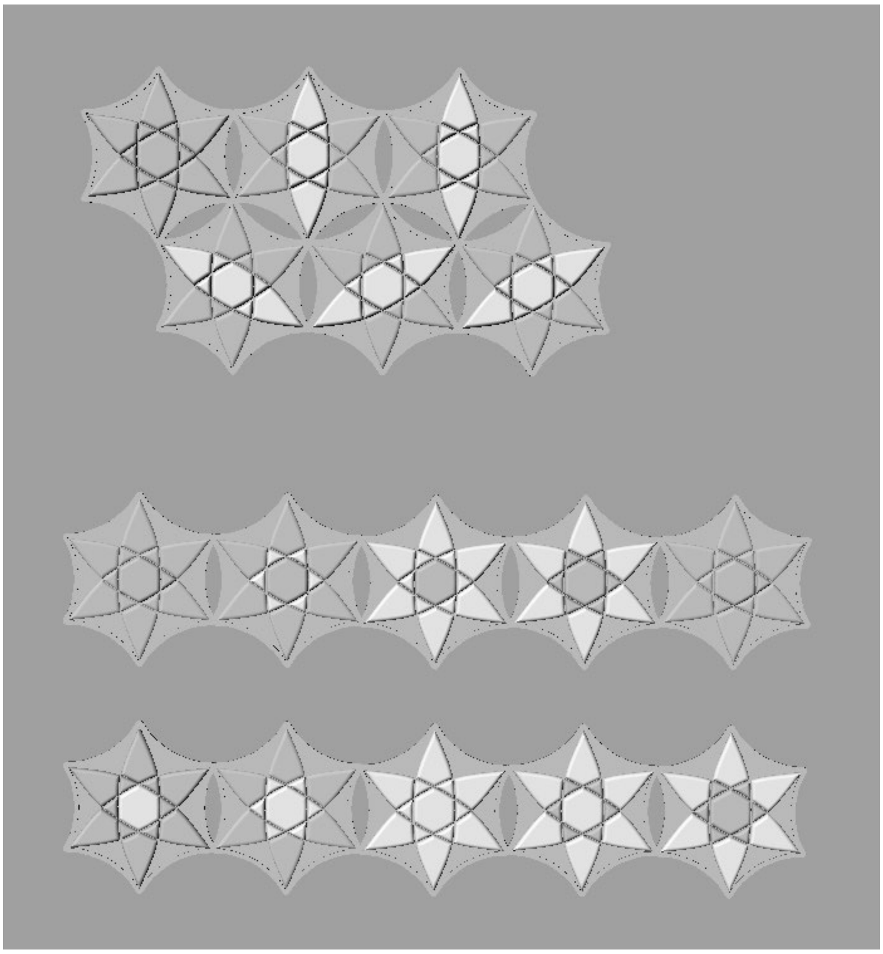

Figure 79: Design (3D) – of shape changing component with inflatable parts (based on the prefabricated module).

I then created the following animations exploring inflation in the sum of elements and potential symbolisms. I was concerned with physical feedback form-finding, and the temporality of shape change: how the actuation looks both at the level one individual module, and in the sum of modules; how the sum of modules might coordinate with each other to produce feedback as a whole, and how this coordination might unfold in time to provide feedback over the course of time- e.g. during a day in the office. The animated clips show the changes happening within seconds, but we can easily imagine the same type of change evolving over the course of an hour, a couple of hours, or the whole day.

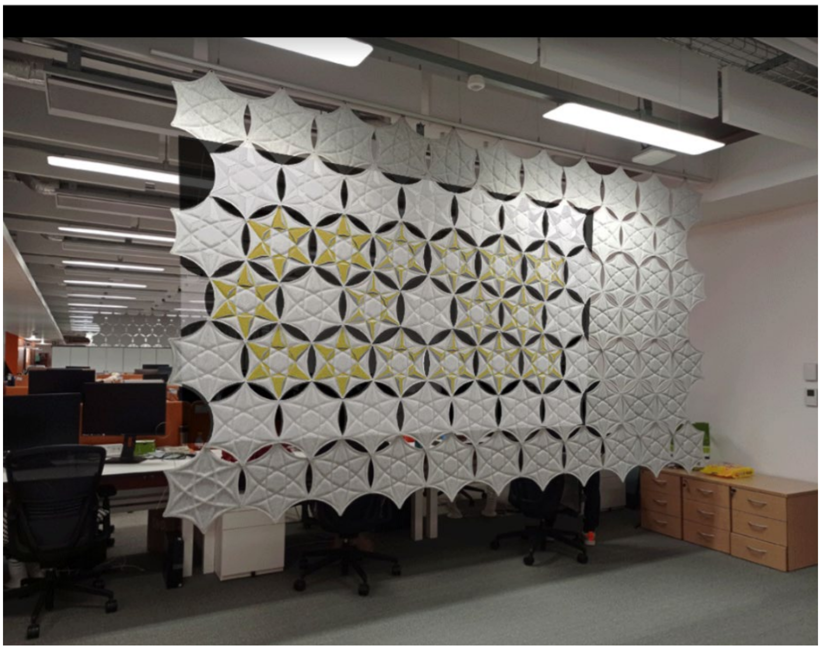

Figure 80: Animating inflation patterns in 3D

The temporal dimension and spatial dimensions of physical feedback provide opportunities to experience data feedback in a radically different way than the ones we are accustomed to (i.e. screens). The main contribution of the design and making of such a calm, slow display is exploring the sense-making and impact on behavior over time in the buildings.

Timing and temporality of feedback amongst clusters of modules also gives room to think about robotics and swarm behavior [333]; bringing a different level of biomimetic symbolism. The key idea is that the actuations in the sum of modules can produce a more complex meaning than the actuation of each module individually; and that the actuation of each module relates or follows the other's in a dynamic way. This can be done through assigning unique IDs in each module and dynamic rules to relate to each other's actuation. A simpler approach would be to centrally control them through predefined actuation timings towards specific events and in relation to specific IDs – i.e. hardcoding when and for how long each module actuates, and in relation to which other module or modules IDs.

The animated clips[155] below explore different variations of modules arrangements, following the above ideas. The first shows the effect of radially expanding inflations. The central module actuates first, with the six others arranged in a circle following with delay. In that system, the leading element is the central one, and the surrounding six are triggered by each response, imitating the spread of fungi in nature. In the second system, the first six modules actuate simultaneously as one; with the next six doing the same after a short delay and so on; creating a linear movement effect. The third system shows the row-wise actuation of elements, creating temporally evolving patterns; each row activates the next. The final one is the more elaborate;

[155] Videos at https://photos.app.goo.gl/2W6g6yjt5MMJtnQ57, https://photos.app.goo.gl/fUUB5vS6mznJyvZV7, https://photos.app.goo.gl/3r86gdptaZwfz6MZA, https://photos.app.goo.gl/KruH6iGnvSxwYxaT8.

whereby each element uniquely responds to the previous one; creating evolving patterns and letters displays.

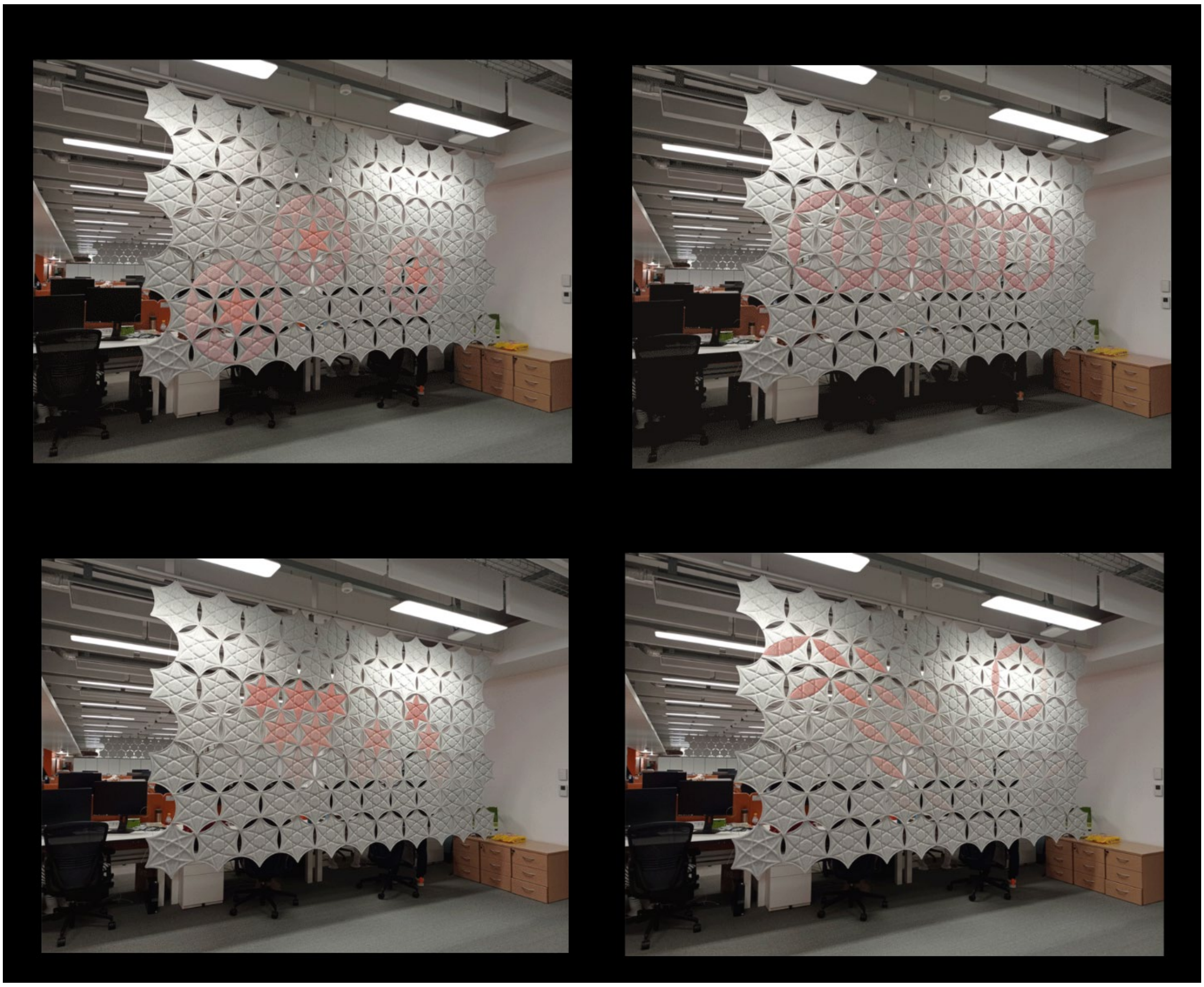

Figure 81: Animated 3D simulation of shape changing modules; testing different patterns and sequences.

These modular animations were used mostly as a tool for an internal validation of concepts and ideas by the researcher, and later to drive the deployment of prototypes for user-evaluation. The ways the above animations are interpreted in terms of feedback by the users will be the core focus of the later studies. These animations were primarily created and used to help me make decisions on crafting and prototyping the modules, shaping a feel of what the effect of future physicalizations might be.

7.3.2. Navigating two material actuation systems (December 2021 – February 2022)

The two systems that derived from the previous stage of concept design are roughly two: one that explores shape change as the folding and unfolding process of planar semi-rigid surfaces composed into more complex shapes; and the second that has inflation and deflation or expansion and contraction (pneumatic actuation) as the core shape-change principle. The first system considers mostly shape memory alloy combined with materials such as paper and fabrics; whereas the second considers a predominantly silicone-based system or potentially composite silicone and fabric, or silicone and vinyl - without excluding the possibility of using different material combinations in both situations. The section below illustrates my first attempts to build actuated prototypes, understanding how materials perform in different physical designs and combinations. At the end of this phase, I make more concrete decisions on what materials I will use, and in what physical design I want to shape them.

I started prototyping actuating artifacts following the above animated design concepts. I was interested to both explore the potentials of folding/unfolding and expanding/contracting systems, dedicating a month for each system while testing the potentials of a range of materials to achieve shape change. I kept the potential of these actuating systems (inflation and folding) to be combined with color-change, using thermochromic pigments. I mostly used felt fabric and muscle wire (flexinol 0.006 HT and 0.010 LT) to achieve folding/unfolding shape change; and custom silicone rubber pouches made from casting silicone in 3D printed molds, inflated using silicone tubes and air pumps to create pneumatics. For many of my crafting experiments, I followed the work of Jie Qi [304]; who provides detailed tutorials of working with muscle wires and how-to's for building basic circuits. The design of electronics will be briefly explained below and in a dedicated later section.

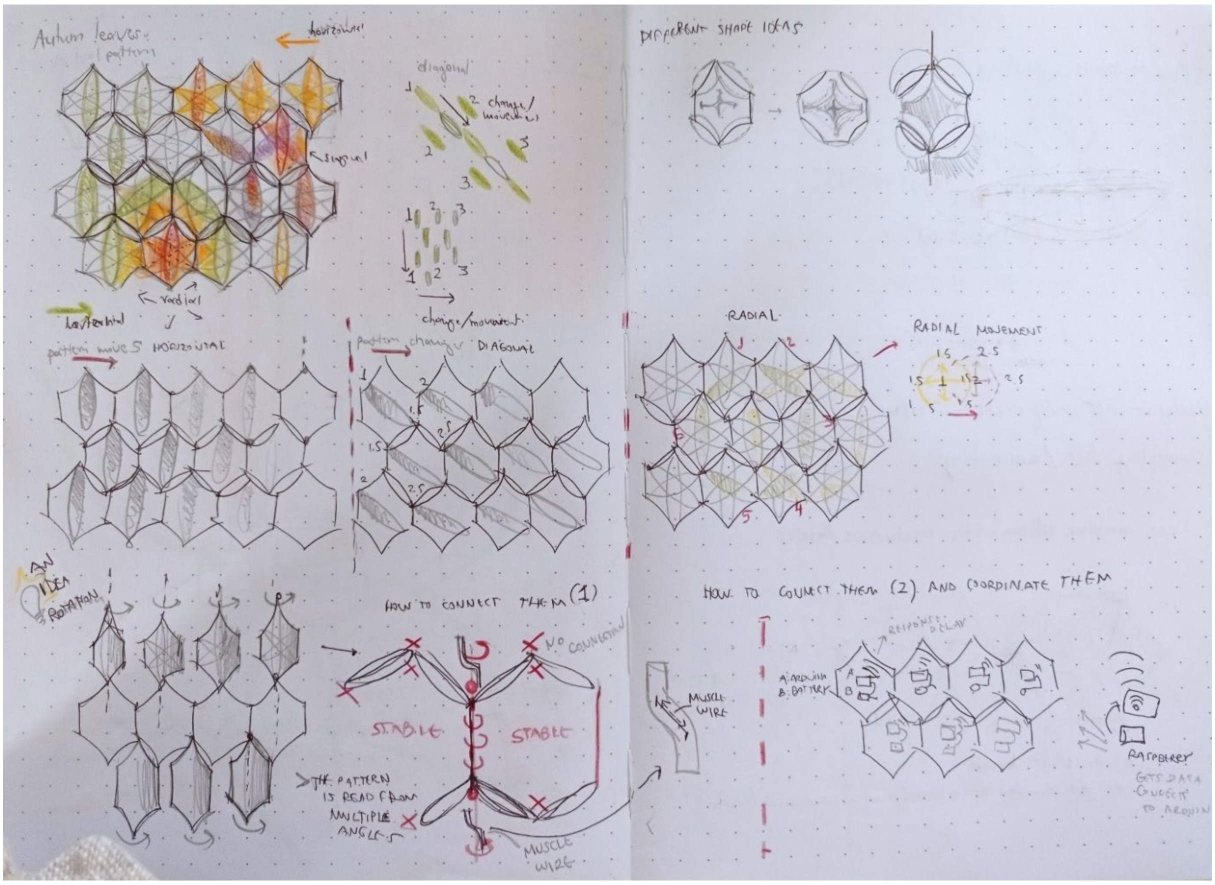

Figure 82: Thinking around the crafting, programming and physical installation of the above shape-changing concepts. Vertical, diagonal and circular physical placement of modules is examined along with the temporal aspects of feedback – i.e. direction and timing of inflation or color change of each module, and the result as a whole - in addition with other installation hacks to create modular mobility for enabling adaptive perspective. Inspired by swarm robotic systems [227,336], each module is conceived having an independent wireless micro-processor (Arduino) with a unique ID, and all essential hardware to operate independently; all of the modules are controlled centrally by a computer (Raspberry pi) who defines their function – e.g. timing of inflation or other shape change- and relationships between them.

7.3.2.1. Folding/unfolding using felt and SMA wires (December 2021-January 2022)

Often what seems promising in 3D works needs further configuration to have the desired effect in the physical world. Creating paper-based real-scale prototypes based on the animated concepts above was the first step to understand the physical affordances of some of these 3D animated concepts and progress with improving their design before starting with materials. Using these paper prototypes, I worked more on thinking around where and how to place muscle wires to have the desired shape change effect; and where and how to develop and place the essential electronic circuit to make it work[156].

Figure 83: Paper prototyping, thinking around shape-change effects and the design of circuits.

The circuits were designed as parallel to use the maximum current of a single power source, prototyped using copper tape and soldering iron. The drawing below shows the principle of parallel circuit and the custom design developed for an actuated module. Utilizing a parallel arrangement, there are different options for developing the circuit (see both pictures); the first using a serial arrangement of SMA wires (following Jie Qi's tutorial) in an overall parallel circuit arrangement, whereas the second is a fully parallel implementation.

[156] See Jie Qi's http://highlowtech.org/?p=1448, https://fab.cba.mit.edu/classes/863.10/people/jie.qi/flexinol_intro.html.

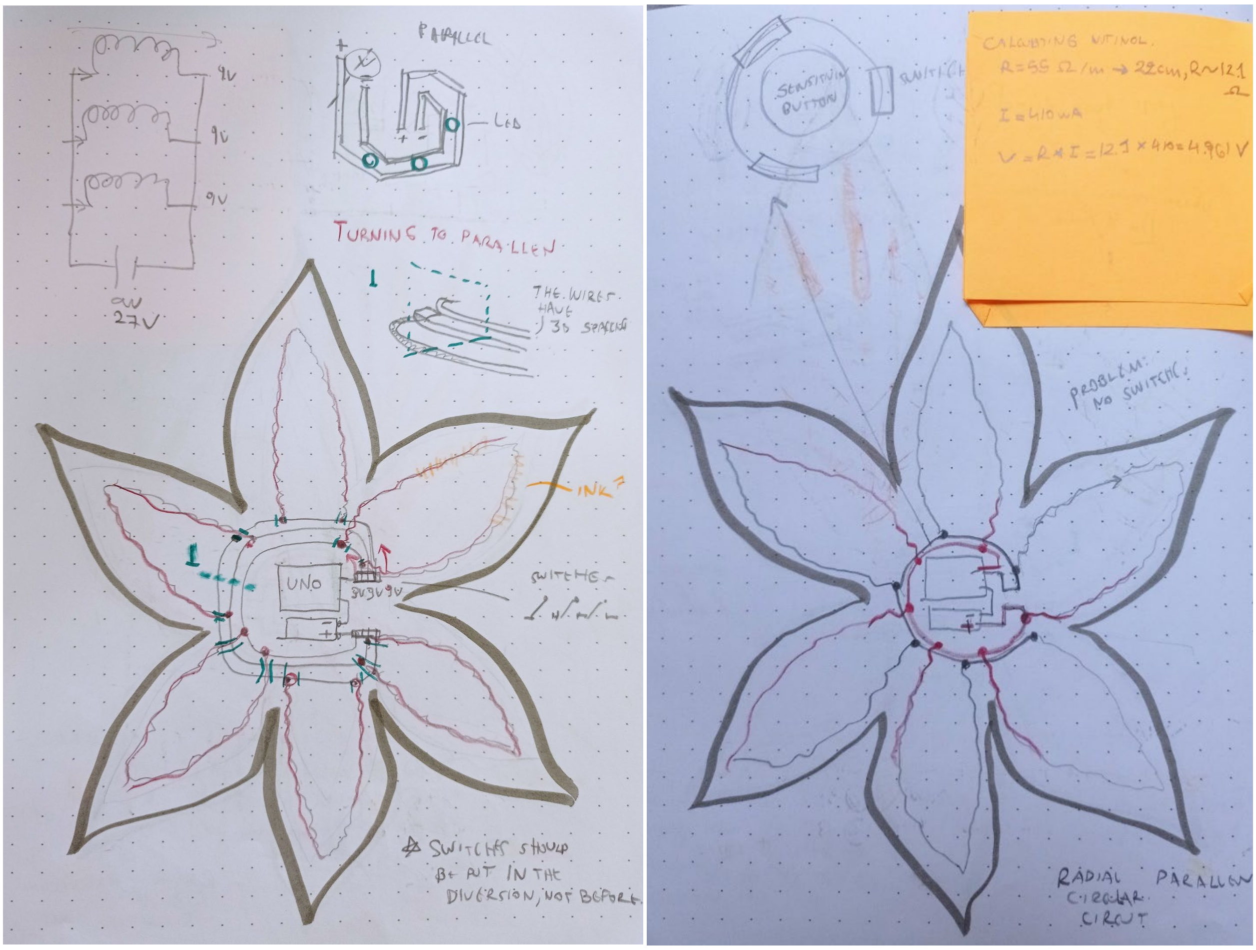

Figure 84: Sketches of parallel circuit arrangements; made-for-purpose versions 01 (left) & 02 (right)

Using the advantages of parallel circuits and while still prototyping on paper, I explored the potentials of having options for tangible user customization of shape- change. I implemented this through creating basic ‘switches’ enabling circuit shortcuts[157] manipulating which of the segments will actuate and which will stay idle. Considering different tangible interactions with users, I developed different versions of hand-made switches (see blue carton in right image below). Using copper tape, the switches would allow users to isolate parts of the model and actuate based on the same current– changing the form and shape-change effect. Another idea was a central ‘sensitivity’ button, which would manipulate the timing of all actuations in each module when pressed. It would require to be connected with the Arduino (placed at the back of each module).

[157] see Jie Qi’s paper switches at http://highlowtech.org/?p=1448

Figure 85: Testing shape changing ideas with paper prototypes (up) and felt fabric (bottom)

Next, I started a series of crafting experiments to understand how to use muscle wire to create shape change, and potentially as a conductive material to create color change (using it together with pigments). To calculate the amount of current needed, the length of the muscle wire and how to stabilize the flexinol wire properly, I followed the extensive tutorials by Jie Qi[158]. In her own words, "*The hardest part about using muscle wire is controlling the amount of current running through the wire. You want to give it enough for a dramatic effect, but not so much current that the wire burns out (and stops contracting)".* Flexinol wire has a consistent resistance per length and an optimum current as specified in the flexinol technical data. One simple technique is to look at the target current from the data sheet and then use Ohm's law (voltage = current x resistance) to calculate the length of wire that is needed to maintain this amount of current based on the power supply. For example, if I am using the 0.006″ diameter wire, which needs 0.400 Amps, and I have a 5V power supply, it will need a total resistance of 5/0.4 = 12.5 ohms. Since the resistance of this particular wire is 1.3 ohms/in, I would need 12.5/1.3 = 9.5 inches.

[158] http://highlowtech.org/?p=1448, https://fab.cba.mit.edu/classes/863.10/people/jie.qi/flexinol_intro.html.

Using the above rule and in combination with overall Energy law (Energy = voltage x current) and the combination of Ohm's and Energy laws (Energy=voltage x voltage/resistance) where suited, I did the following experiments as shown in pictures below[159]. Each experiment[160] helped in gaining knowledge on how to work with different materials, and problems and opportunities in achieving certain results (the relevant tutorials that assisted with making these experiments are mentioned below each case).

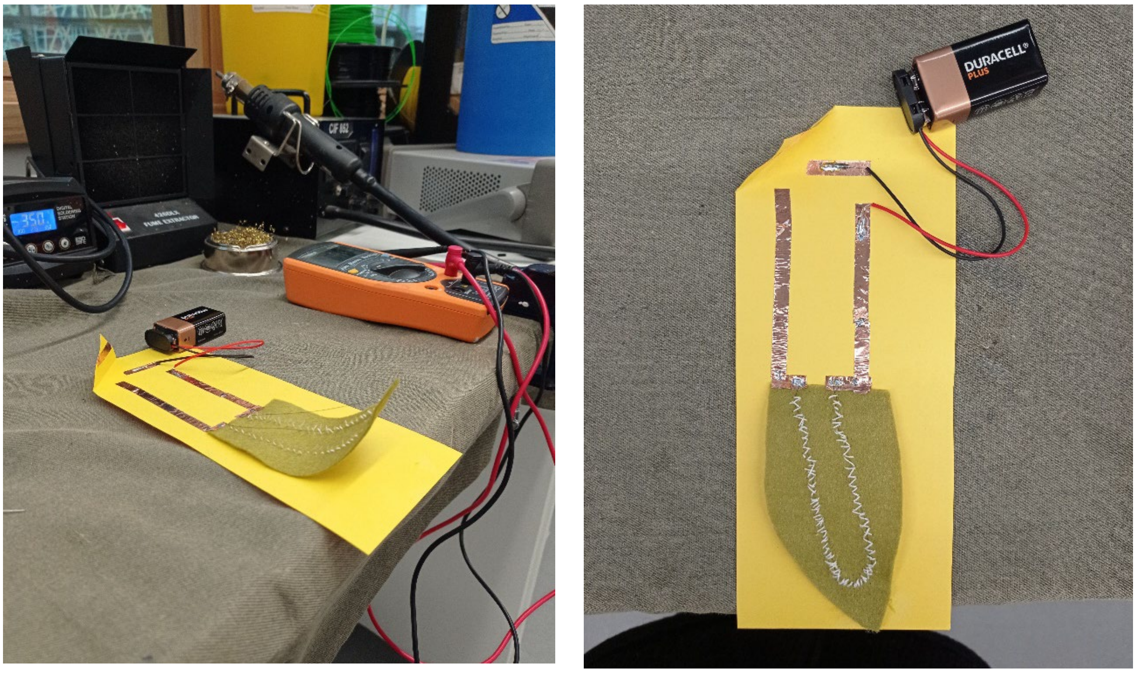

Figure 86: Testing shape change using flexinol muscle wire (Flexinol 0.006HT) sewed on felt fabric, a simple copper-based circuit using a 9V battery including a folding-paper switch.

Opportunities & Challenges Copper tape works fine to create easily adjustable circuits, but you need to make sure you have a double-face conductive copper tape and apply solder in all joints to make it work. Soldering the muscle wire was not easy either, but the trickier part is to keep it in place on felt. Using simple thread does not often work that well as it gets slowly loose or burns out. Warming up (training) and actuating the flexinol wire was relatively easy; the effect was desirable but it felt that the 9V battery is too strong for the amount of wire used. Using lower voltage can potentially create a similar effect without burning the thread – will be tested in future experiment.

[159] Videos of different voltage & current combinations: 1) 12.5 Volt at 0.650 Amber: a faster, dramatic response: https://photos.app.goo.gl/BAjp6q9oFBr8C7Wh6; 2) 8.5 Volt at 0.650 Amber: a slower, less dramatic but observable response. Testing parallel circuit and each segment independently through creating shortcuts (potentials of having switches to isolate segments manually): https://photos.app.goo.gl/mHnbNTFexZ1zsPMD9; 3) 8.5 Volt at 0.450 Amber: very slow and subtle response: https://photos.app.goo.gl/BtgzkiKsKz6V5XRN6

[160] Video at https://photos.app.goo.gl/mHnbNTFexZ1zsPMD9

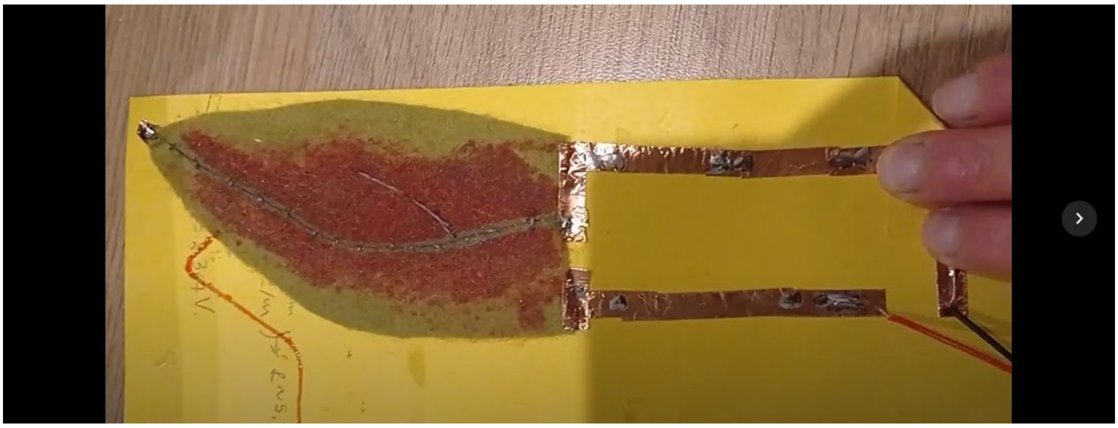

Figure 88: Testing color change of thermochromic pigment on felt using conductive thread and copper tape (Flexinol 0.006HT). I painted a small area of fabric using SFX red pigment (31 degrees transition point); diluting the pigment in transparent acrylic paint. I controlled the current (9V battery) with a simple copper-based circuit including a switch.

Figure 87: Creating a folding flower; The 'flapping crane' experiment tailored to my design case. Testing folding of a flower-shaped felt fabric using SMA wire (0.06HT) in a serial circuit made out of copper tape. The folding effect was tested using a 9Volt battery and at 13,5Voltage/ 0.45Amber current using an adjustable power supply machine.

Opportunities and Challenges In both cases, the current was as strong as it should producing the desirable folding effect without burning the SMA wire or the thread that was used to keep it in place; and was maintained this way after many repetitions. The felt fabric’s weight was nicely balanced with the length and type of SMA wire and the amount of current; the folding effect is achieved, and then the fabric returns to place when the current stops - due to gravity. Still, if positioned vertically, the effect is not the same. More current will be needed to create the same effect if the SMA wire is ‘sandwiched’ between fabrics or used with semi-rigid fabric or a combination of fabric and paper to be able to stand in a vertical manner.

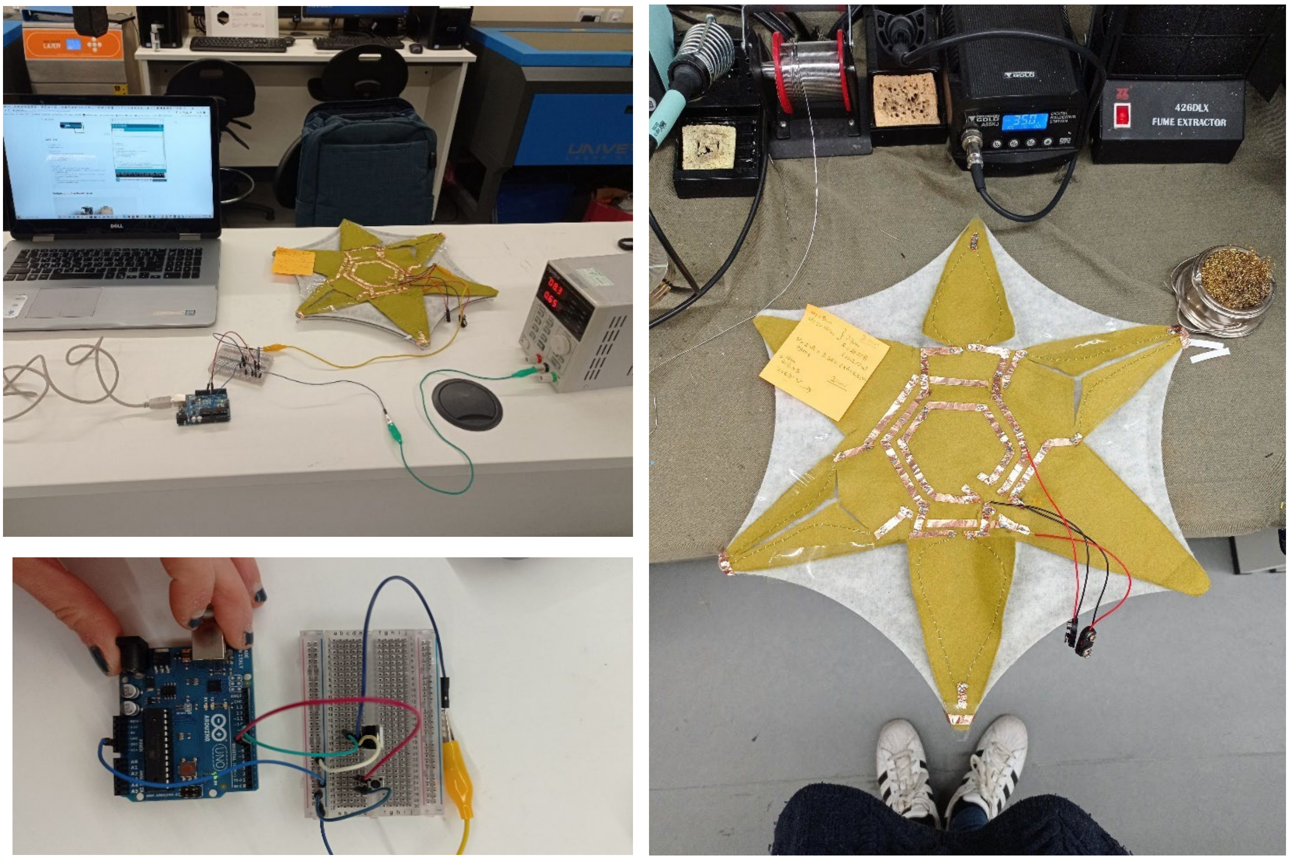

Figure 89: Creating a parallel circuit using copper tape, felt fabric and muscle wire (Flexinol 0.006HT), illustrating different folding and unfolding potentials. Different folding patterns are combined into one prototype; and different current & voltage combinations were tested (in parts or the whole of the parallel circuit) to evaluate the shape change effect.

Opportunities and Challenges Enough heat to create dramatic shape change effect makes tangible interaction risky. The length of the SMA wire has to be enough to overcome the weight of the felt fabric and create the desired effect; but at the same time, there has to be enough felt material to allow the return to the initial shape. The above experiments illustrated that the shape change is subtle and potentially not noticeable, and the return to initial shape not always achieved on time and as desired.

7.3.2.2. Expanding/Contracting pneumatic system using silicone(January -February 2022[161])

During this phase I explored the potential of silicone to be used for pneumatic actuations – e.g. expansion and contraction of soft elements. These initial material experiments helped solidify the workarounds and the use of silicone to create inflatables, and the understanding the actuation potentials of such soft elements e.g. inflating, contracting, pulsing and changing color. I designed and 3D printed (PLA) molds (see first attempts in the pictures below) to cast silicone rubber in (Ecoflex 0030) to create custom inflatable elements that would then be glued on the prefabricated felt components using Sil-poxy glue. I followed tutorials[162] to create the inflatable silicone pouches – e.g. creating them as two separate elements to be glued using silicone. I manually inflated the silicone pouches, testing for air-leaks and the effect in different material thicknesses; at this stage, they were all treated as independent silicone elements to be then glued onto the prefabricated module.

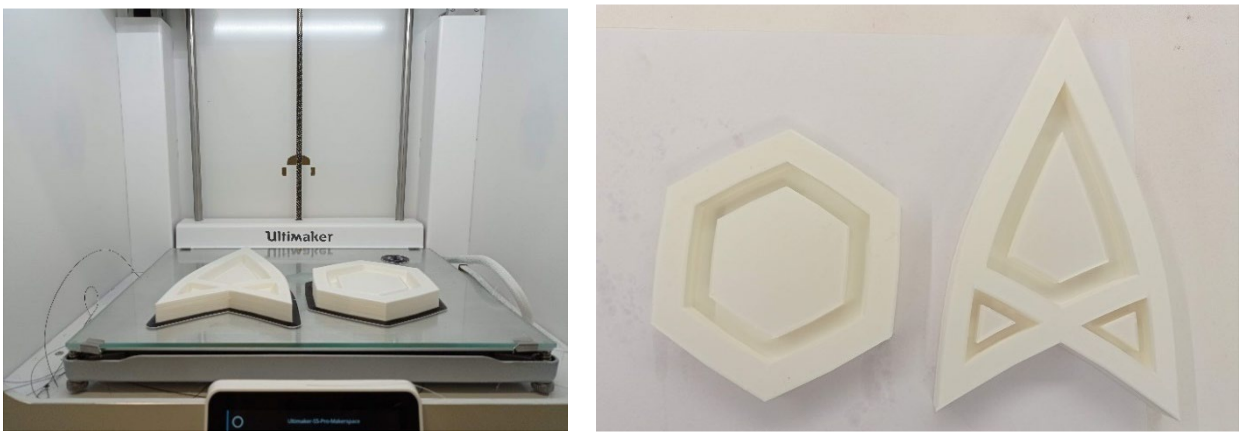

Figure 90: Designing and 3D-printing molds in different thicknesses to cast silicone to dry. Pouches were produced by gluing the silicone parts together using silicon. Initially produced silicone was too thick (the molds were too deep) and the sides were too narrow, resulting in insufficient attachment of silicone layers and air leaking.

[161] I was at the peak of extreme nausea during pregnancy, which slowed down progress.
[162] Such as https://www.instructables.com/Air-Powered-Soft-Robotic-Gripper/

As a fast experiment[163], I used thermochromic pigment (red color, transition temperature 31 degrees) in some of the thinner silicon elements I made and tested the color change effect using a hair drier (see pictures above). It worked, giving room to consider the use of thermochromic pigment in thin layers of silicone.

Figure 91: Testing inflation in silicone-made pouches and thermochromic change of thin silicone layers (colored with thermochromic pigments) when heated.

I further explored form, material and actuation aspects of silicone rubber. I worked on 3D-designing and 3D printing (PLA) my molds to find the best way to create the desired shape parts, compose them into bigger units, and the optimum material thickness. I created the silicone inflatables by casting silicone in the PLA molds, let it dry for 4 hours, and then combining the result with a flat silicone rubber part of similar thickness – gluing them together using liquid silicone rubber. The tubing (2mm) was inserted into the final inflatable through a small cut, and then further repaired in case any leak was observed using liquid silicone.

I designed molds in smaller scale, exploring the potential of creating smaller pneumatic elements (with the prospect of combining them to compose a bigger shape) with different shape-changing capabilities. For instance, the star-shape mold has been done following a tutorial[164], with the intention of creating a soft actuating divider with air-powered folding and unfolding parts. These experiments didn't continue further after I realized the complications of testing each individual silicone component and then connecting and coordinating them, as well as the difficulties in developing and embedding the electronics.

[163] Videos at https://photos.app.goo.gl/MXNSGsUYTkvyWNhQ6 and https://photos.app.goo.gl/EXa4PgW1RyRYHbg78.
[164] https://www.instructables.com/Air-Powered-Soft-Robotic-Gripper/

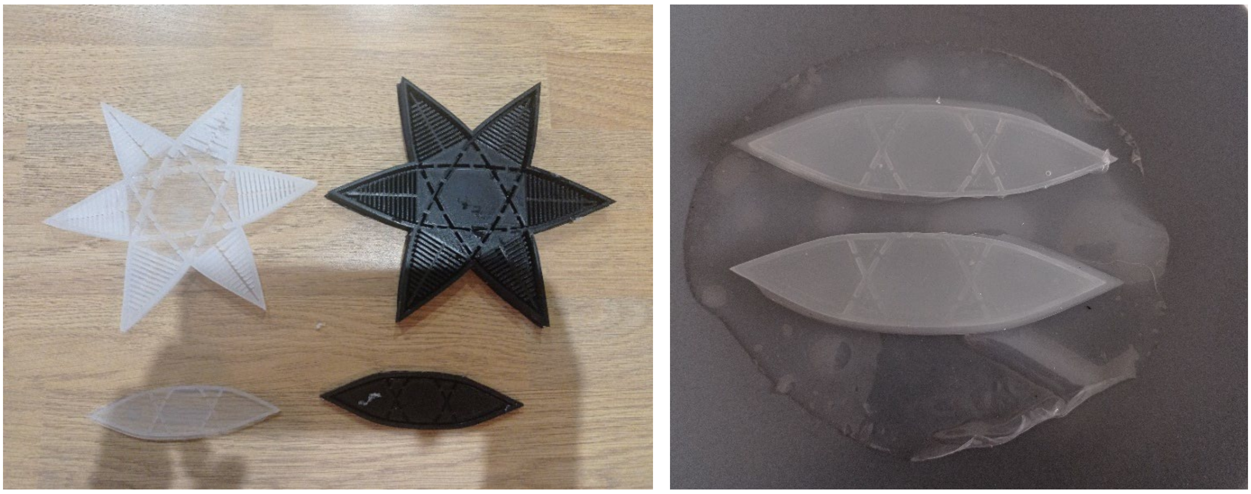

Figure 92: On the left, the mold and the result. On the right, glueing the silicone layers using more silicone.

I worked in developing the electronics circuit, using example tutorials[165] as a guidance. I used a valve and an air pump in each circuit, connecting them with a wireless Arduino. The aim was to be able to control the inflation/deflation rate, but also keep them in an inflated mode for longer periods of time. Noise produced from the pump was addressed first by covering the pump with woolen textile and enclosing it in fabric; later on, with enclosing it in foam.

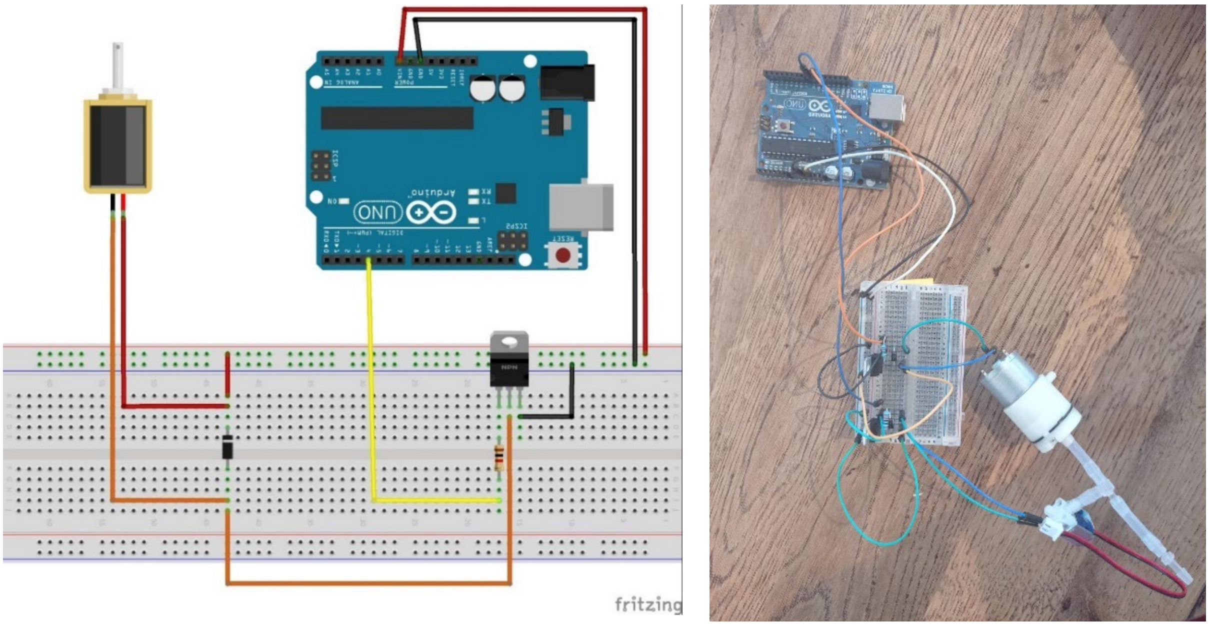

Figure 93: The circuit diagram and implementation using one solenoid, a 220 resistance with a IN4007 diode. In the image on the right, it is replicated using two solenoids (a pump and a valve).

[165] https://core-electronics.com.au/guides/solenoid-control-with-arduino/, https://bc-robotics.com/tutorials/controlling-a-solenoid-valve-with-arduino/#:~:text=Start%20by%20connecting%20one%20of,9VDC%20power%20on%20the%20breadboard

I spent the rest of the month working on the prefabricated felt components, figuring out ways to combine the silicone inflatable parts together, glue them on the felt component (using silk poxy), insert and positioning the tubing and include the electronics and air pump system in the back side. At this stage, the inflatable parts were all independently inflated – leaving space for potentially controlling their inflation/deflation independently and not as a whole. Additionally, space has left for combining these silicone inflatables with color changing pigment, either placed on felt fabric or mixed within silicone. The latter – color-changing silicone – is an open design space, which I will try to address with the next experiments. Below, an early attempt of combining silicone shapes and solenoids together, thinking of the overall material thickness and actuation effect.

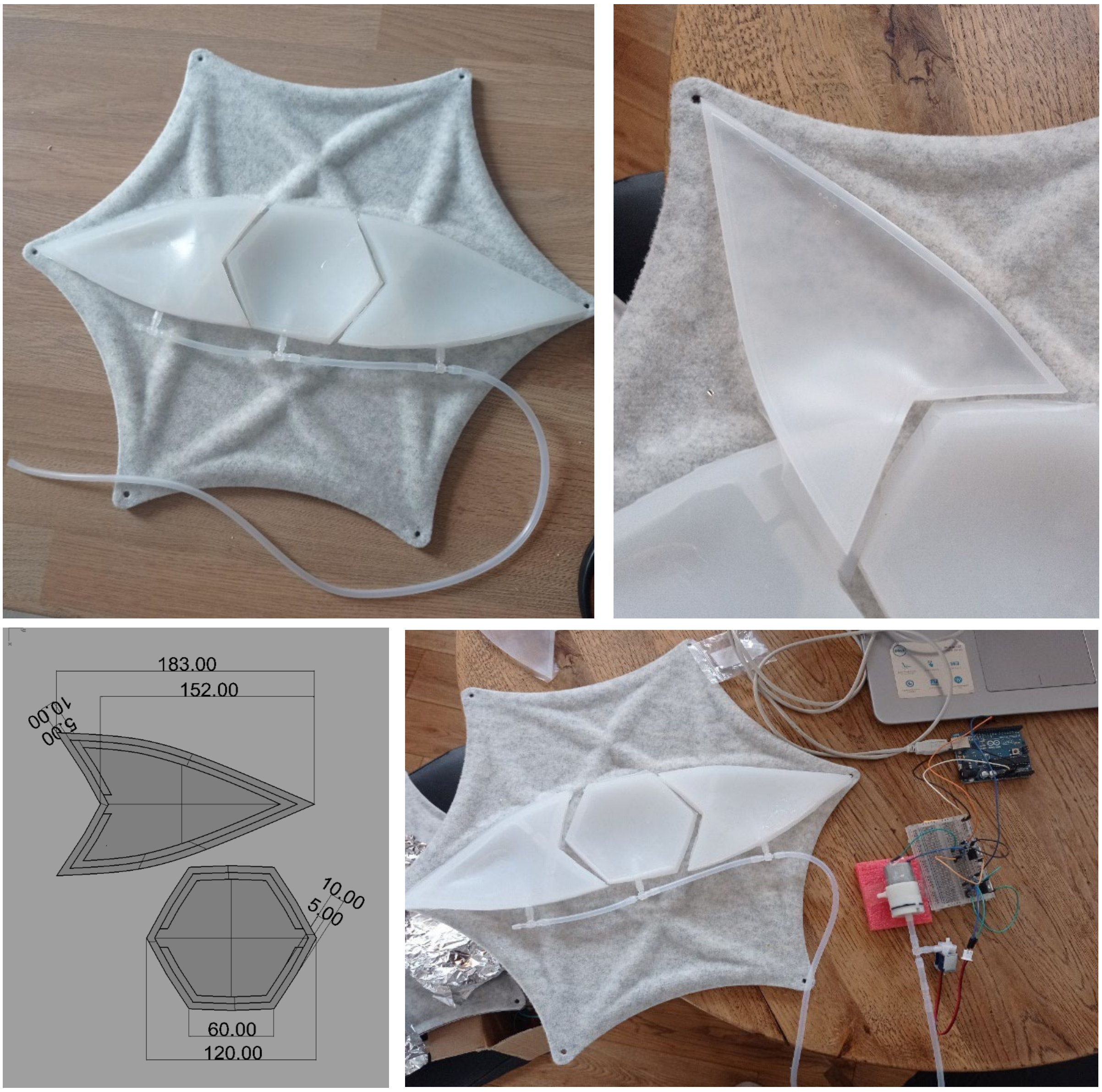

Figure 94: An early attempt to combine three silicone pouches into a bigger structure and connect them with tubing and the electronics. After a few printing & designing experiments, the final size of the molds was fixed (see 3D with dimensions in mm above). The silicone rubber is cast in the molds and is left to stabilize (4 hours) and then combined into larger shapes using more silicone.

Opportunities & Challenges The fact that the pouches are independent create opportunities to be programmed to actuate independently; but at the same time, this adds complexity. The pouches are interesting to touch, creating opportunities for considering tangible feedback. The weak spots are along the edges of the pouch, where air leaks often happen, especially around the spots where the tubing is inserted in the pouch. The middle component is still considered to potentially function as a button, from where the sensitivity of the system – i.e. how fast it responds to data streams, or how much it inflates – can be controlled by the users.

7.3.2.3. Summarizing key learning points and making decisions on materials & systems.

After this initial material and design and making phase, I evaluated the potentials of each actuation system - e.g. felt & muscle wire and silicone inflatables - to choose the direction of further development.

The felt & muscle wire system had the advantage of being silent, on the other hand, the visual effect of the actuation is limited, the system is fragile – i.e. tangible interaction might better be avoided - and the shape change is not always successful – i.e. returning to the initial shape is not always accurate. Although I can overcome these concerns with the right choice of felt material & design pattern, and the careful knitting of SMA wires; there is bigger concern around the excessive heat needed to power the actuation and the fact that the room divider will very likely be touched by the users of the space. Even with the careful covering of SMA wires, the chances of overheating and getting hands burned cannot be dismissed.

The silicone inflatables on the other hand resembled the opposite properties. They are promising in terms of the extend of the actuation – i.e. can be heavily inflated and have a dramatic effect- they are robust – can be touched without the fear of burning and are interesting to touch, although the edges may leak- but quite noisy as they require pumps to operate. Moreover, they are easier to replicate – i.e. producing silicone pouches is not a hard task once the 3D printed mold is fixed.

Both systems had limitations in terms of the color change using thermochromic paint; silicone is nicely mixed with pigments, but as it is a conductive material, it needs to be in very thin layers in order to change color.

Moving forward, I decided to continue working with the silicone inflatables as the actuation impact seemed more promising and safer for the users and resolve leaking through further design experiments and the pumping noise effect using insulation. Color change using pigments is treated as an open design challenge. The next section further experiments with color change, solidifies electronics and circuits design (hardware), and the design, making and assembly of silicone pouches.

7.3.3. Working on pneumatics: combining inflation with color change (March- April 2022)

This next design research phase described here builds upon previous experiments and decisions made upon basic form factors and material combinations, solidifying form and shape changing aspects using silicone, electronics and circuits; while exploring different ways to create color change – e.g. using pigments and different conductive mediums, and later using LEDs.

The images below illustrate the attempts to create a first fully functioning module using an Arduino, and a circuit developed on the breadboard developed as described above. The pump and valve are placed in the back on the prefabricated module. The silicone pouches are glued in the front. In the earlier stage, each pouch had its own tube connected to the pump, with the prospect of being able to inflate it individually using more solenoids in the back (more valves to control each pouch individually). In this stage below, all the pouches are connected to each other through silicone tubes into a big inflatable shape comprised by 3 pouches and the middle component.

Simplifications like this had to be made due to time constraints; as I had limited time left to complete my design & evaluation phase of my PhD (approx. 1 year left post-lockdowns) and since I was the only person working on it, testing and prototype replication was slow. The initial ideas of a more complicated solution whereby each pouch operated on its own were downgraded to a single inflatable shape; similarly, the middle button function for adjusting sensitivity of response to data was put aside for the time being. What was still interesting for me was to combine color change capacity with inflation; and I decided to dedicate the next weeks to exploring this.

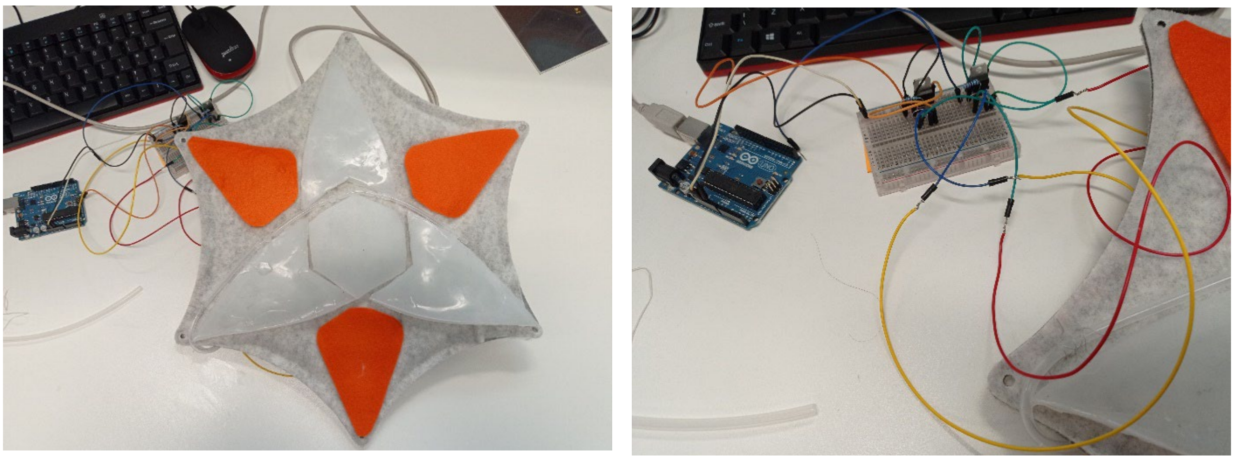

Figure 95: An example functional arrangement of silicone pouches. Although functioning, it was still complicated to put it together and control the inflation amount; pointing towards working on more simplified future versions.

Moving forward, I colored liquid silicone using thermochromic pigments before casting it into molds, producing thin-layered colored rubber. I then combined the colored parts together in bigger shapes. Next, I started attempting color change of the painted rubber using electronics; facing a series of problems. Silicone is heat resistant and non-conductive; in principle, it has to be mixed with other materials to become less heat-resistant and conductive.

The fact that it is stretchable when inflated makes controlling color change challenging; on the one hand, as the rubber material is stretched, it changes color on its own (becomes more transparent). It also becomes thinner and therefore easier to heat. On the other hand, the fact that it is stretchable makes the embedding of electronics such as copper tape, conductive threads and heating pads more challenging. It comes down to solutions such as heating the air contained in the silicone pouches or using conductive liquids[166] to create color change in silicone; the latter was dismissed as I thought that it might be dangerous in case of leakage.

Figure 96: Combining silicone and thermochromic pigments

I did a series of little experiments with changing the thickness of the silicone material to observe color change through heating it. I used heating pads, conductive thread and copper tape to create heat when powered by electricity. The thickness of the material was a

[166] http://www.interactivearchitecture.org/skin-colouration-in-silicone-wearables.html

determining factor in its color changing capacity. Most of the experiments worked with silicone <=1mm thickness, but anything above that threshold created problems. Silicone is highly none-conductive (it often works as insulation of circuits), and as its thickness grows the material becomes hard to heat. Moreover, it is hard to combine heating with inflation of the surface; although the silicone stretches and therefore becomes thinner which enables faster color change, it loses the contact with the heating medium. Mixing metal liquids/antistatic agents like Tuball 602 can increase conductivity of the silicone rubber if mixed when liquid; still, the problem of failing contact with the heating medium/electric circuit when inflating exists in this case too.

Many options were considered to overcome this problem, such as using liquid metal to create stretchable circuits in order to heat inflated silicone, using conductive thread stripes or conductive mesh embedded in thin silicone layers – again to create the potential of heating while inflating and therefore color change while inflating. After a round of experiments, the idea of using thermochromic pigments was abandoned as neither of the above methods brought great results in terms of achieving controlled thermochromic change, while the fabrication of the material & system was time-consuming. Additionally, any effect of color change was hard to control, often weak, and, once it has been achieved, hard to bring back to original state. Additionally, the desired color change would be from transparent to color – exactly the opposite of what most of the pigments offered. Instead of insisting on thermochromic pigments, the use of LEDs was considered, as they offered post-fabrication programmability.

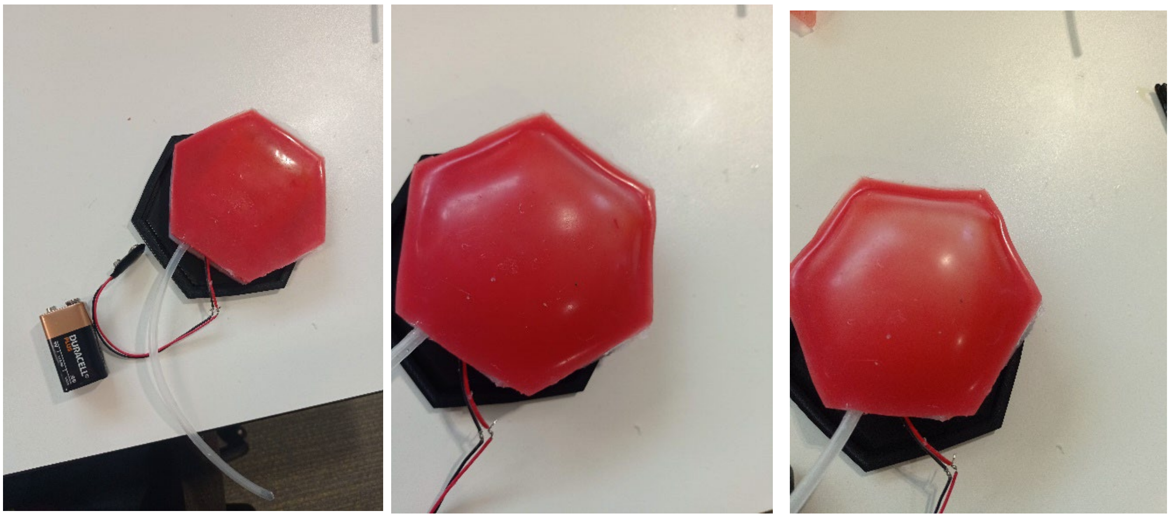

Figure 97: Experiments with a heating pad in a silicone pouch. The color change is subtly visible in the last picture. The heating of the air contained takes time; the heated air stays trapped so inversion of the effect also takes a very long time.

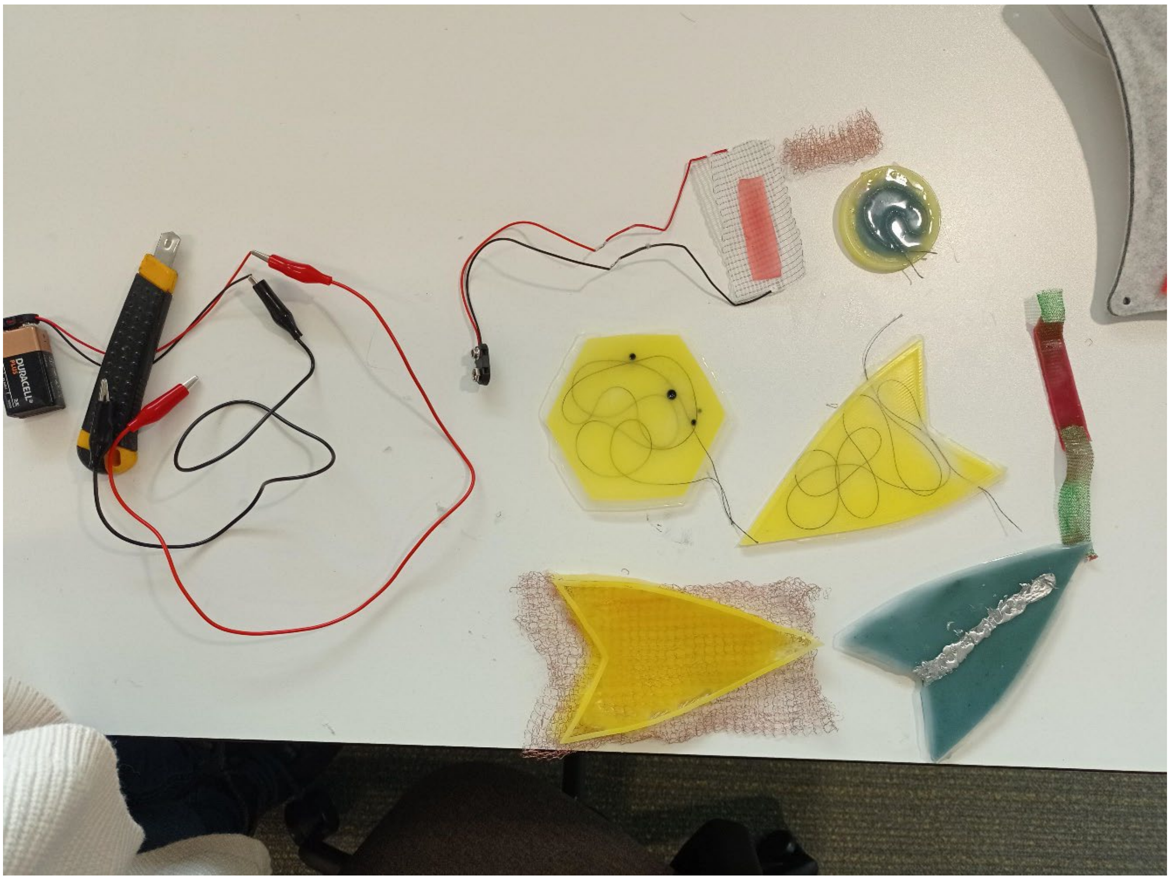

Figure 98: Different experiments with heating pads, conductive tread, conductive mesh and liquid conductive metal embedded in thin-layered silicone rubber.

I used the NEOpixel 30 LED strip, which I further modified for the needs of the prototyping. Programming these LEDs is relatively easy as the library includes many tutorials; with each LED being independently programmable but also programmable as a strip. It is also easy to change the physical appearance of the strip by cutting it in indicated joints and re-joining them with soldering iron. The final strip was glued under the silicon inflatable using liquid silicone.

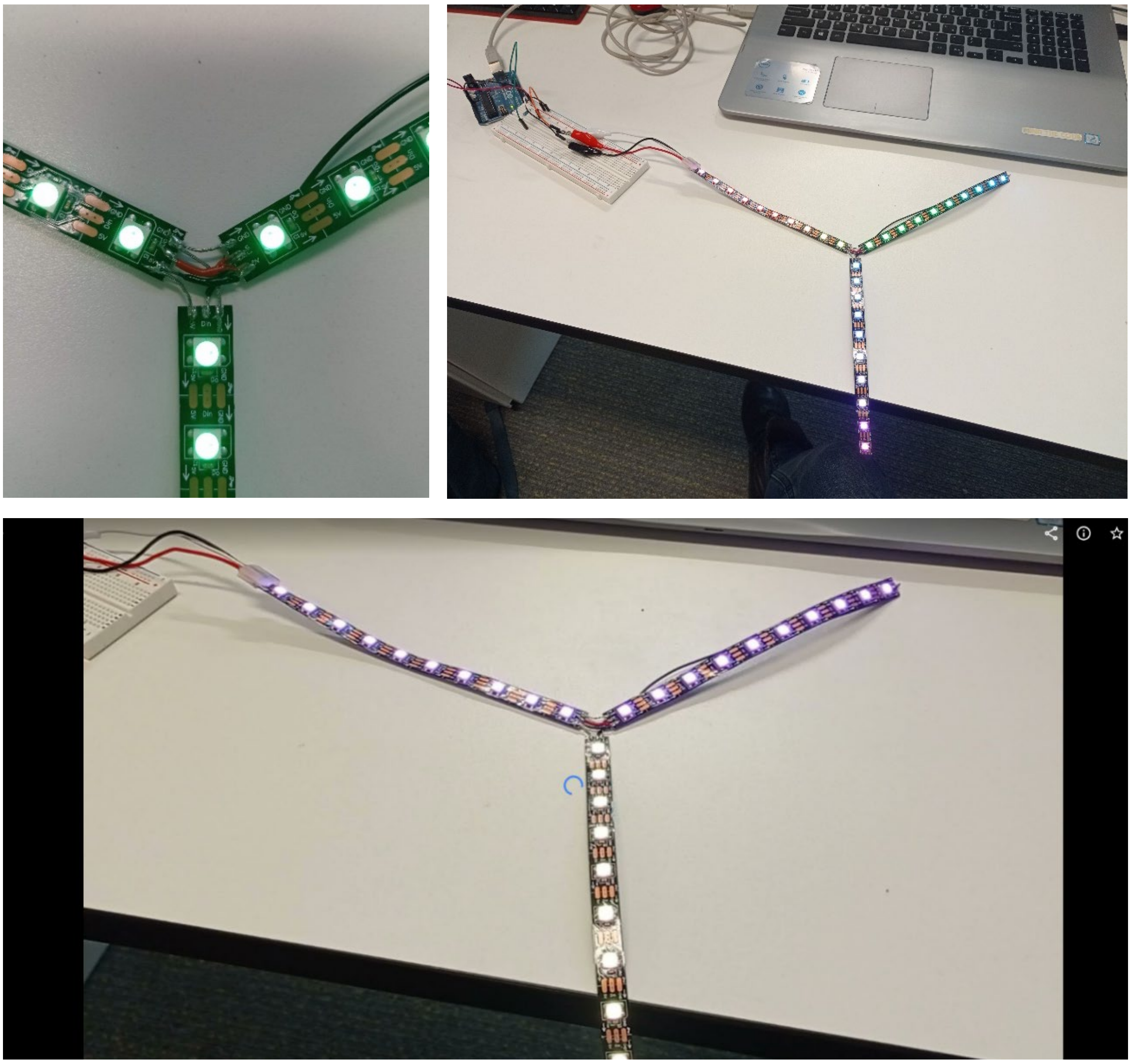

Figure 100: Re-assembling the Neopixel LED stripes and trying the Neopixel animations library (Arduino Scripting); video at https://photos.app.goo.gl/bXba5imtKTt8KNLB6

Figure 99: Attaching the LEDs on the back of the silicone pouches, and creating a final module that inflates and illuminates/changes color using the LEDs.

The integration of LEDs created new opportunities for user interactions and tailored feedback. Being able to programmatically set and change color while inflation takes place provides the option to treat these two as both independent and complementary communication systems. The ways that inflation and color change are combined and synchronized can vary, leading to different feedback interpretations of the feedback. Users can have the option to control the color themselves, customizing the actuation of the room divider. These ideas drove the development of the software to control and synchronize the actuated modules; and the content of the evaluation studies.

The foundations for the final hardware and software that operates the inflatables were established in the beginning of April; with the main software development phase lasting from middle April to middle of June 2022 with the help of Dr Jan Kucera. The software has undergone a range of changes; with the final version of it described in the following section.

7.3.4. The making of the final ActuAir prototype (May 2022 – June 2022)

During this phase I finalized the design and making of the module. I took decisions to enable fast replicability of the components and finalized the hardware and software operating them. I decided to simplify the fabrication process, and instead of a more complex 'star' shape I settled on creating 'teardrops' (see figures below). This organic shape followed the design principles of biomimetic structures, imitating soft muscles or expanding body parts of jellyfish or amphibians. The pouches were comprised out of two (2) pointed elements and one (1) middle element combined into one shape and sealed together using more silicone rubber; then positioned on the prefabricated felt components (using silk-poxy) following the design pattern of the prefabricated components. The teardrop's advantage is that it was easier and faster to make using the already developed 3D printed molds, in comparison to previous more complex shape ideas. The LEDs were attached in the back of the inflatable drop, sandwiched in between the silicone pouches and the prefabricated felt component; the whole mechanism was then glued on the prefabricated felt component. In that way the LEDs didn't pose a problem during the inflation of the silicone, while the double layer of silicone rubber created a light diffusing effect enhanced when inflated, hiding the LED. Titanium dioxide was also used to whiten the silicone rubber and decrease its transparency, to allow better light diffusion.

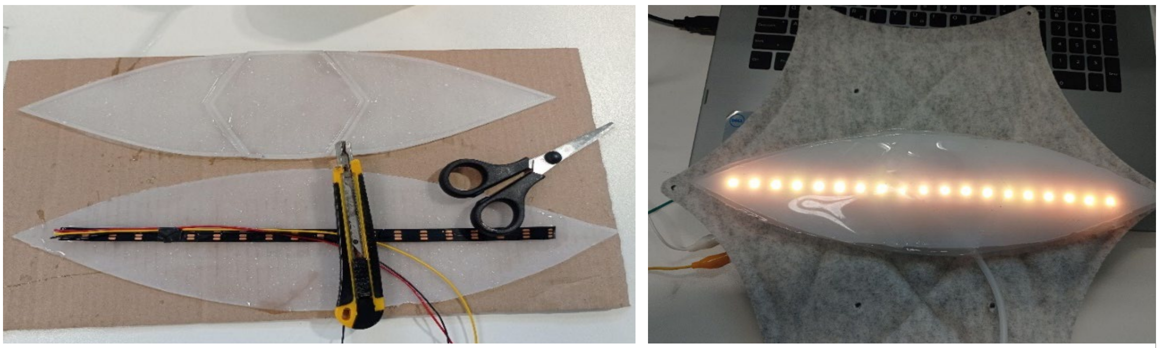

Figure 101: The making of the teardrops; on the left, assembling silicone rubber parts together into a pouch, on the right, positioning the pouch on the felt component with the LED stripe on the back of the pouch.

In terms of the electronics to operate each module, the following decisions were made. I used Wireless Arduino (Arduino Uno Wifi Rev02) to allow the wireless communication with the local server via WIFI. Each of the modules operates with a wireless Arduino connected to a local server built on Raspberry pi. In that way no cables are needed (appart from the power source), allowing the free movement and assemby of the modules in differrent locations in the building – as long as they are in relevant proximity with the router. The wireless Arduinos are integrated behind each module, enabling them to act as stand-alone and in coordination with other modules.

All the rest of the electronics were also placed in the back of each prefabricated module. A whole was opened to allow the tubing and cables to pass through the other side of the module. The electronics were soldered on preboards or breadboards and then all attached to the back of the felt component using thread and glue. The Wireless Arduinos, breadboards, tubing and cables were glued and sewed in the back. The pumps were placed into foam to reduce the noise. Hardware remained well-stabilized and exposed in the back.

The wireless Arduinos control the solenoids – e.g. air-pumps and valves in each module. Arduinos control the air-pumps and the time of inflation – i.e. correspondigly, the amount of air pumped in the pouches – and the valves - i.e. how long they stay inflated, and the time of deflation. The alternation of these two mechanisms results in pulsing. Air- pumps are noisy, so inflation and pulsing are the most noisy functions; while valves – staying inflated, and deflation – are silent. Air pumps and valves also control the function of LEDs – e.g. what color, color transitions, and timing of color appearance.

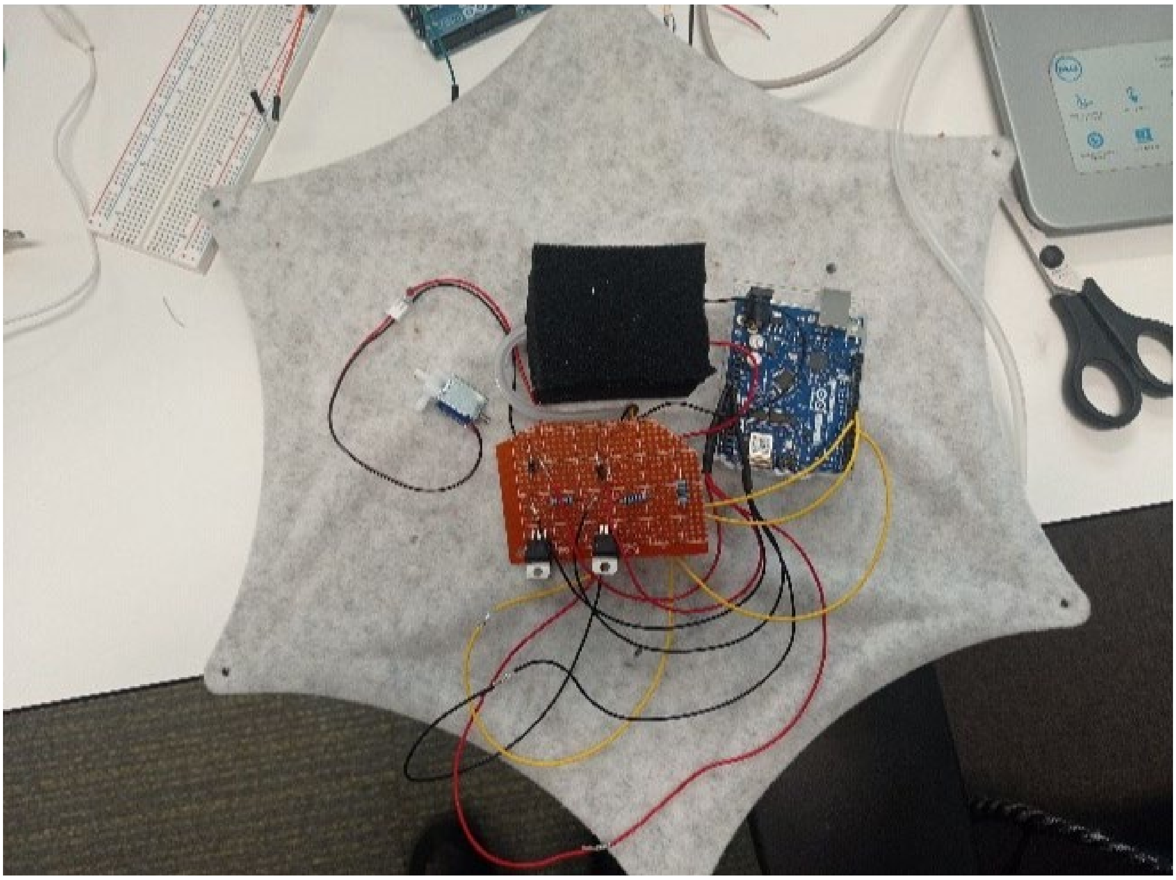

Figure 103: Top picture showing the circuit with one solenoid; bottom one all the electronics attached in the back of the module. The pump is enclosed in black foam.

Figure 102: Example of a module inflating, with a series of color animations. Video at https://photos.app.goo.gl/LyF5vyu61E5aLkJw6

Figure 104: The final fabricated modules

Each Arduino has a specific ID number (based on their static IP), which is hardcoded in the server's script and is also physically marked behind each module as a number. The server is then able to control them based on their ID's, creating different responses based on air quality data streams.

The software is a server application that runs on Node.js, React and Axios. The server is fetching Air Quality data (CO2, temperature, humidity) from Urban Sciences Building; made available through an open API. Data includes real time and historical (24-hour timeframe) sensory readings (CO2, temperature, humidity) of the building's rooms. The server fetches data at the start and then at 30 second intervals; and communicates with arduinos at the beginning (on start, initial value), and every time there is a change in the values. Depending on the correspoding values, the arduinos signal to inflate or deflate, and change color (the exact rules will be described).

The server also provides user control on the function of wireless Arduinos through control panels. Through this control panel, the user can choose one or more Arduinos (based on ID) and choose to display the current CO2 (or temperature or humidity) value, or animate the historical values of CO2 (past 24 hours). These data then are used by the Arduinos, which trigger the inflation/deflation and animate LEDs color/brightness.

The final server software developed has a control panel with two main functions (see pictures below):

- It allows users to select the room (room ID as provided by the API) and the realt-time data stream (CO2, temperature, humidity) they wish to physicalize using one or multiple components (choosing Arduino's IDs). The modules were set to inflate based on the first readings; with the amount of inflation relevant to the reading of CO2 sensor - i.e. the equivalence would be 5 seconds of inflation for 200ppm CO2 – and then stay inflated. They were then inflating more or deflating in coordination with the changes in CO2 levels – e.g. if there was a deterioration in air quality, the modules were inflating more (at the same equivalence rate as described above); if there was an improvement, they would deflate. Inflation/deflation was used to represent the relevant change of air quality. The LEDs were set to represent the actual level of air quality; values from 400ppm-550ppm were displayed as green, 550ppm-650ppm as yellow, 650< as red.
- It allows users to select a room and a number of components, and displays the historical data (measurements over the past 24hours) in these components in a sequential animated way. The above principles of inflating/deflating and changing color were maintained; there were combined between x number of selected modules. Each module responded to a specific timeseries entry, followed by the next etc.

The above basic functionality was evaluated with a group of experts (see next chapter). Following their suggestions and for the purposes of future studies on feedback perception, a second control panel was developed which allows the users to set a custom colors in different intensity in real time, combined with controlling inflation/deflation of modules. It also provides customizable color animations such as color fading (gradient color change from no color to color, or the opposite, at a custom time interval), or smooth transition from a color to another color (again in a customizable way – i.e. it can be set in repetition, and at a chosen time interval).

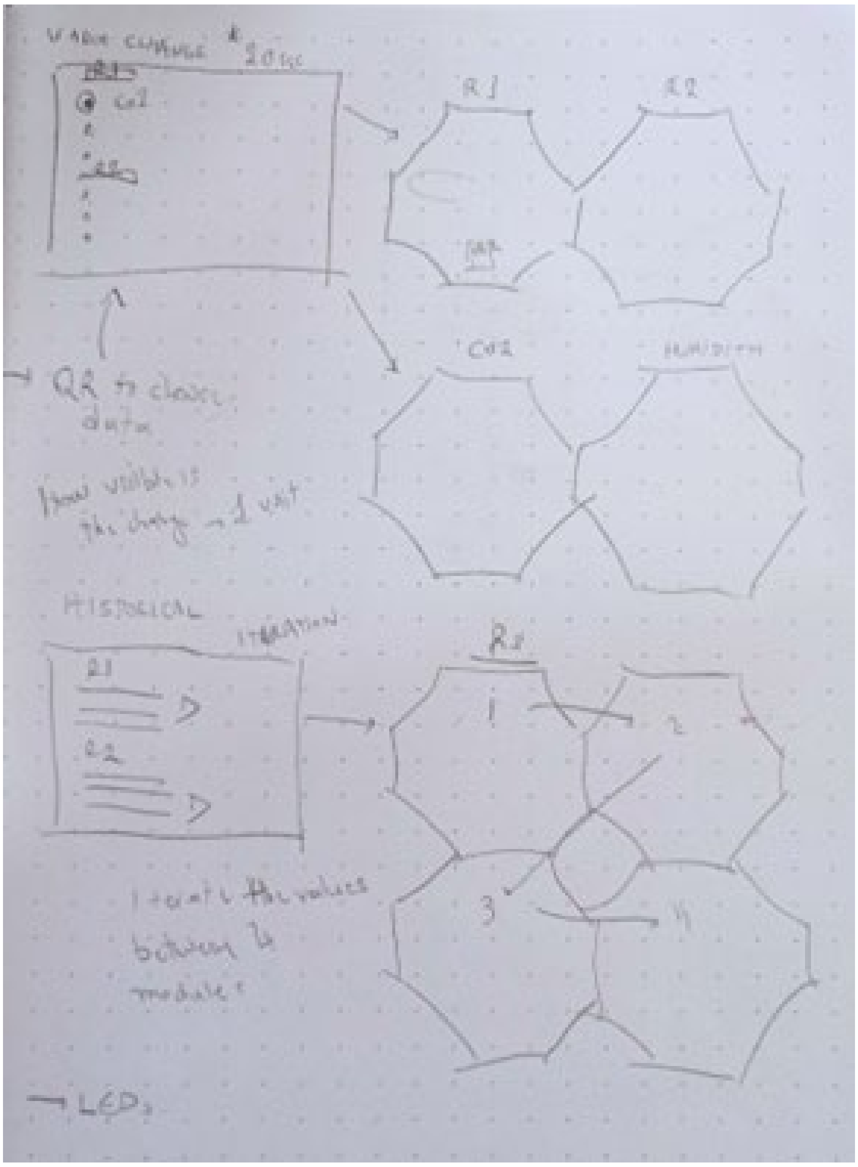

Figure 105: A sketch illustrating the modules operation principles. Starting from above, each of the two modules represents CO2 in different rooms. The sketch right below shows the option of one module representing CO2 values, and the other humidity, for the same room. The final bottom drawing explains the sequential physicalization of CO2 data between 4 modules; with the first displaying the first entry, the second the next one, etc.

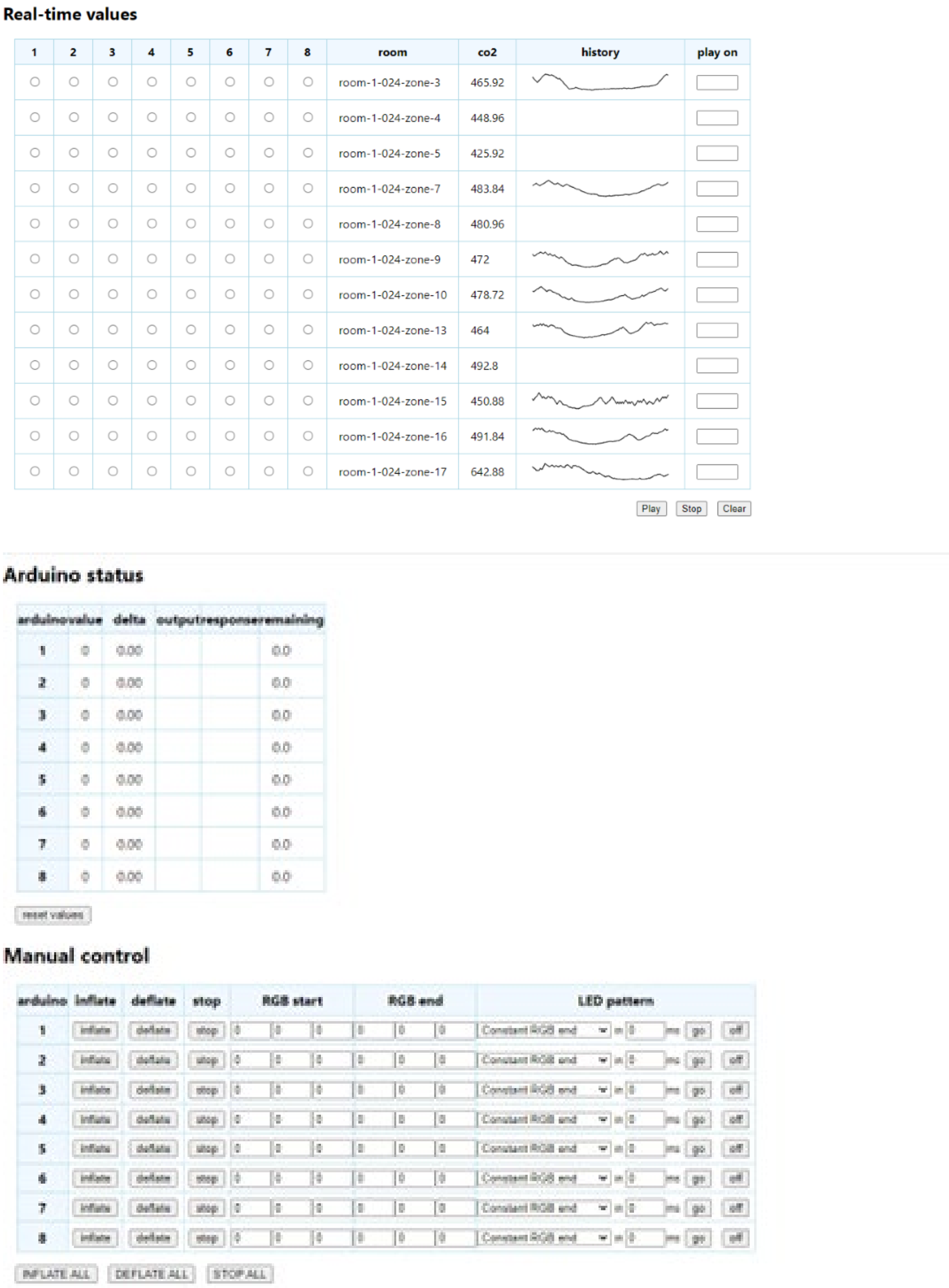

Figure 106: The web software interface to control the modules (data streams and Arduinos). First image at the top is the main control panel of the app, allowing the selection of rooms and modules to display either real time data, or timeseries data. The second image is a table showing the responses of Arduinos – to assist with troubleshooting & debugging. The bottom image is the example of the second panel which allows customizable colour setting and animations, combined with inflation/deflation

The software[167] was additionally developed to be able to potentially use Luftio's[168] API – a portable air quality sensor which can be used at the workplace and at home; to be able to

[167] Code can be found at https://github.com/jantheman/AQPump

[168] see https://luftio.cz

extend the studies at home if needed, or physicalize data per individual desks (the building's API shows CO2 per defined rooms and areas, not per desk).

Figure 107: The pre-set function of modules; video at https://photos.app.goo.gl/xxRJRLYaRspGymzP9

Opportunities and Challenges The modules are obviously noisy – although the pumps are enclosed, they still produce lots of noise. Moreover, the amount of inflation can cause issues such as breaking the pouches. Although the pouches are robust enough, the constant inflation to their limits can cause damage or small leaks. It is a thin balance between achieving an interesting result and maintaining them in the longer term.

The image (and video) above showcases the function of the module. The silicon components inflate proportionally to the initial measurement, deflate when there is an improvement in AQ, and inflate when there is deterioration. The initiated shape change is small when a small change occurs and becomes bigger when a critical change occurs. In that way, the modules produce a lot of noise only initially when inflated; then the noise is limited. Similarly, the colour can be green, yellow and red in relation to the CO2 ppm levels. This can be defined as the pre-set function of the modules; but all the described rules will be subject to user testing. Pulsing (rhythmic inflation and deflation) has been abandoned for now as it generates a lot of noise; but it will also be tested with users. Beyond its pre-set function, the module can be further customized by users in terms of when & how much it inflates, colour selection, and colour animations (see images below).

The users will be able to move around these modules and assemble them as they think its best, and experience air quality data in different parts of the workplace. The users will be able to select the room or rooms from which they want to view data, data streams e.g. CO2 or humidity etc.; and the ways they want to view the data – i.e. real time or timeseries – and will be able to coordinate the actuation of the modules based on their IDs. Users can also potentially manipulate the color and color animations for each of data representations. The result would be a modular & customizable (physically and digitally) soft actuating barrier that provides physicalizations of data in place. The long-term aim of installing the modules in the lab would be to raisee awareness on air quality, and support wellbeing through this awareness at the workplace. The next chapter will focus on the evaluation of the installation with experts and users.

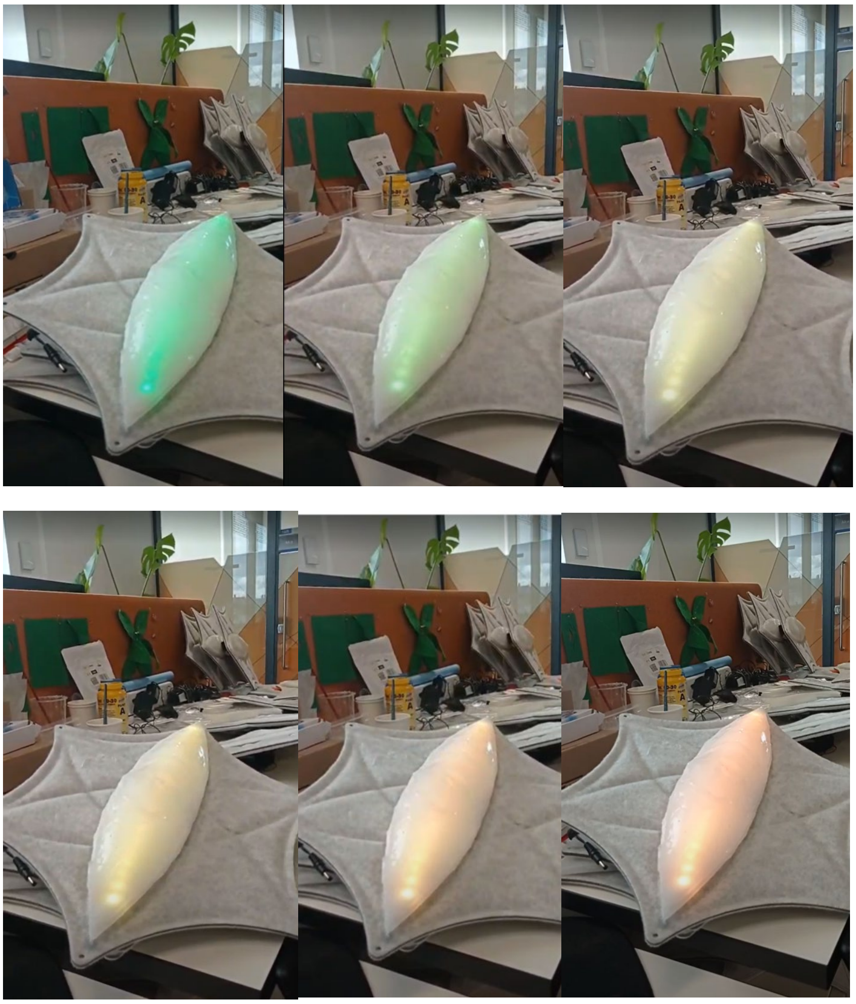

Figure 108: Example animated color change from green to orange; video at https://photos.app.goo.gl/xkDqut6f6bWnnLtQ9

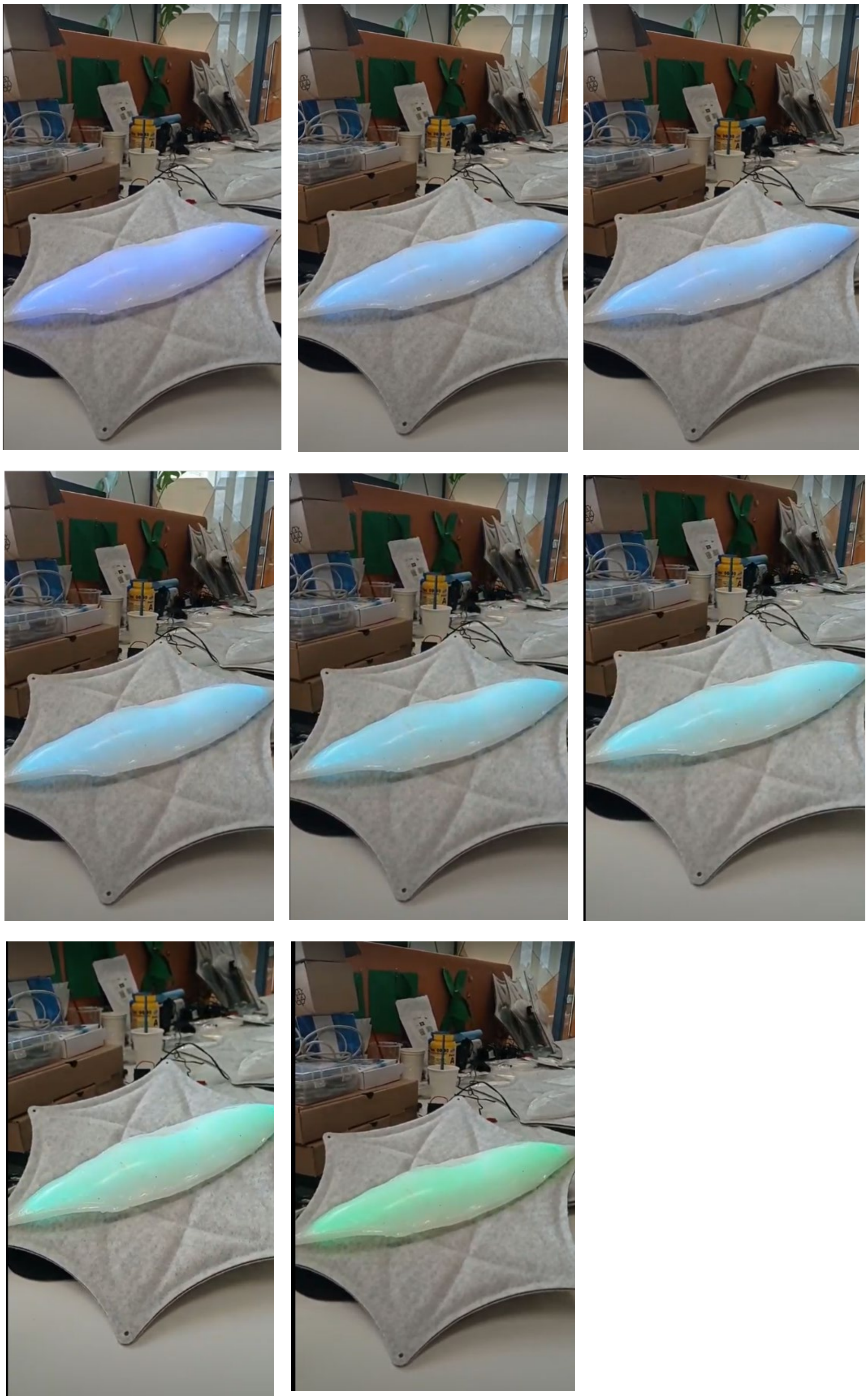

Figure 109: Example animated color change from blue to green
https://photos.app.goo.gl/W8Zxrcn69NZzent38

Figure 110: Example modular arrangement

7.4. Design Reflections

Target of this work is to create responsive workspaces that raise awareness on air quality AQ levels to enhance the wellbeing of their users through interactive data physicalizations enabled by soft robotics. The above chapter illustrates the learning experiences obtained through the making of an actuated room divider. Responding to

- (RQ3) What design interventions in workplace buildings can support data experience for wellbeing?
  RQ3a: What feedback design can support wellbeing through experiencing data in the buildings?

I illustrated the design research journey of working with different actuated materials, the lessons learned around how to work with them and the failed experiments that present future research opportunities. Due to COVID-19 restrictions, this design research journey had to be kept within a specific time limitation; therefore, decisions were made to simplify the design and making of the modules. Still, the design journey had meaningful takeaways; and it can provide a meaningful ‘how to and what to avoid’ for designers & researchers that want to explore the world of soft robotics in interior architecture for data awareness and accessibility. Presented as a series of failed and successful design experiments, the above chapter can be a meaningful guideline for replicating such systems, an example of undergoing experiments or testing workarounds, or a guide towards expanding the research field through further examining my failures. Summarizing, the discussion presents key takeaways of this design research phase in terms of lessons learned and summarizes main avenues for further design research.

7.4.1. Summary: The ActuAir room divider

The final prototype is a customizable, modular shape-changing modular display that physicalizes changes in AQ data streams of a sensory-rich building (obtained via an API). The prototype consists of eight custom silicone rubber pouches with embedded Neopixel LED stripes, attached on eight prefabricated fabric modules (see Figure 104 B); forming a customizable modular room divider (Figure 104 A). The silicone rubber pouches inflate and deflate based on different AQ data levels – choosing between CO2, humidity or temperature data. In the default set up, the amount of inflation is proportional to the selected data stream – e.g. inflation increases when CO2 increases. The inflation effect is enhanced by the embedded LEDs, which obtain a green-to-red color range proportionally to preset AQ levels. LED animations and gradual color transitions are manually controlled and not part of the default set up (details in supplementing materials).

Each module operates with a wireless Arduino connected to a local web server built on Raspberry pi (Figure 104 C). The server is fetching AQ data (e.g. CO2, temperature, humidity) from the building’s API, and wirelessly communicates with the Arduinos which control the air-pumps and valves for each module - e.g. the amount of air pumped in and out, and the time they stay inflated or pulsing – as well as the Neopixel LEDs function – e.g. LED brightness, color and color animations. All electronics (e.g. Arduinos, air -pumps and valves, preboards, cables) are integrated at the back in each module, enabling them to act as stand-alone and in coordination with other modules.

The server application provides a webpage with a control panel which enables the researchers to choose different data streams – i.e. CO2, humidity, and temperature - from different building sensors; choose to display real time or historical data; choose which modules display which data; and manipulate feedback – i.e. manually control inflation/deflation of a given module, manually control LED color range and speed and repetition of animations (see supplementing material). Utilizing the control panel to dynamically configure feedback, the researchers evaluate aspects of the display’s perception and interpretation, such as the experience of inflation as CO2, the choice of color range to represent improving and deteriorating AQ; and the timing and the synchronization of these inflation and LED color change.

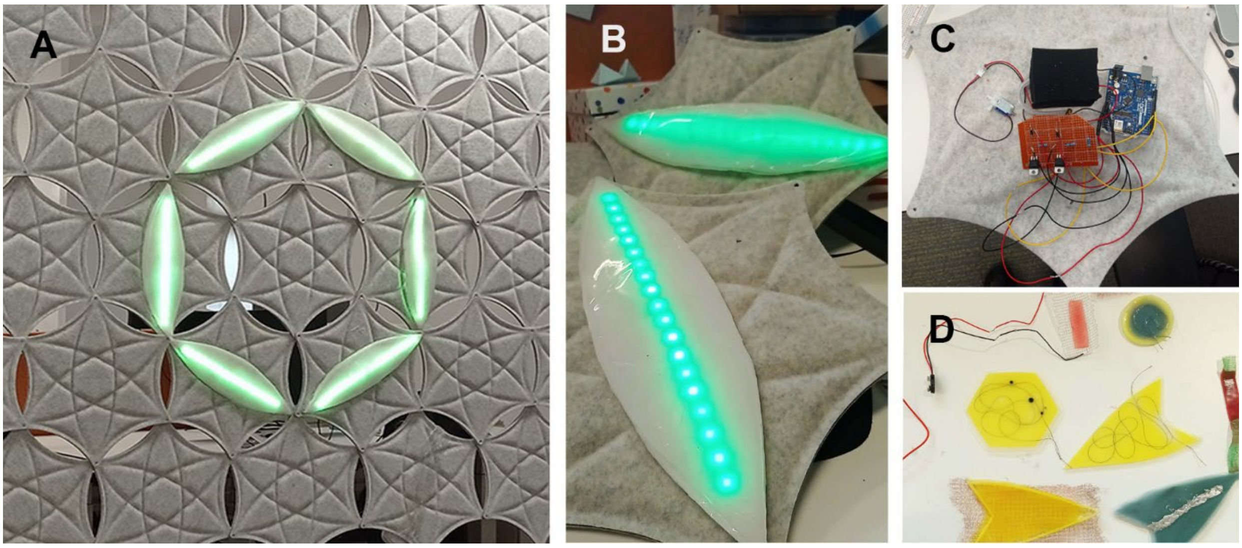

Figure 111: A: the prototype deployed; B: the inflatable pouches with embedded LEDs; C: hardware in the back of each module: a wireless Arduino controlling a foam-sealed air pump and a valve; D: work in progress, experiments with silicone thickness, thermochromic pigments and conductive materials.

Biomimicry is conceptually at the core of the design of the intervention. Biomimicry drove the prototype's design and making process; the form of the pouches and the choice of materials was heavily inspired by natural organisms (for example the Portuguese Man o' War). The metaphor of breathing– translated to inflation and deflation – is key behind the conceptualization of the prototype.

7.4.2. Challenges as opportunities: lessons learned and future work.

7.4.2.1. Workarounds, geometry design, materials

Form (3D geometry) & materiality (material selection) are two interdependent systems to achieve effective shape change. The work of Alexandra Ion [164,165,340,401] on interactive structures & auxetic geometries illustrates this, as geometry becomes a key instrument to achieving interactive complex structures using soft plastics / elastic materials. She refers to mechanical metamaterials, consisting of analog and digital metamaterials; the latter supporting swarm logic in the structure – i.e. where the impact of the collective action of all modules is bigger than the isolated ones. Similarly, in the examples of using SMA wire and fabrics – the heaviness and rigidity of the fabric chosen and the ways the SMA wire will be embedded impacts the strength and result of actuation effect [243,244]. In pneumatics, the use of more rigid materials such as vinyl or plasticated fabrics can create impressive shape change; moreover designing and replicating the geometry can be relatively easy through laser cutting – see the Printflatables [325]. The use of silicone is also interesting; silicone has a very different effect in pneumatics and is also relatively easy for structures to be replicated through the use of 3D printed molds – see SoRoCad [37].

Beyond creating geometries for metamaterials, using 3D models can be meaningful for animated simulations and expert or user evaluations, bridging the gap between design research and participatory design. In my research journey, I used these animated models for my own guidance and concept evaluation; but these could be also used for engaging and evaluating with users – using video-recording or spatial projection techniques.

7.4.2.2. Pneumatics in context: dealing with noise

Challenges of expanding the soft robotics agenda for the workplace are infrastructural constraints to support the function of robotics in interior spaces. Soft robotics usually operate with motoric actuators and air pumps, which produce noise. Avoiding air pumps and noise has been achieved through electrohydraulic actuators, which have a different fabrication process (e.g. using air-sealed soft pouches filled with dielectric silicon oil) but can potentially be combined with other materials such as silicon pouches to produce different shape changing effect. A solution is presented by PITAS [60] – whereby inflation is achieved through chemical interactions in silicone pouches.

Alternatively, ways to noise-seal the air pumps while maintaining the system's portability and adjustability will be an ongoing challenge. Portability of pneumatics is an issue, although platforms such as FlowIO [339] seem to partially overcome this issue while minimizing noise – with an appropriate design and using the most silent pumps possible, noise is still present but not as prevalent.

A different point of view is to utilize noise to raise awareness when an actuation happens. Using it within limits and under specific moments, noise can grasp momentary attention and engage users – in the same way that noise and vibration of our phone caught our attention.

7.5.2.3. Composite Silicone: reflections on color-change, conductivity and sensing/tactile capacity

The above design research work briefly explored the potentials of silicone to be combined with thermochromic pigments and conductive materials. As my experiments were rather brief, its worth doing further research on the matter. The key points that my work established are:

- Silicone can be very well mixed with different types of pigments – i.e. thermochromics; titanium dioxide etc. – without losing its elastic consistency and insulative capacity. Potentially there are types of mediums that can be mixed to enhance conductivity of silicone.
- Thin layers of silicone offer more potential to be combined with conductive materials & electronics. Silicone can be well combined in stretchable sheets with conductive fabrics[169], stretchable electronics[170], metal meshes, or optical fibers nets.

Recent relevant research on creating composite silicone & layered materials is illustrated in PITAS [60]. Two separate silicone mixtures are created, one using Tuball 602 and Ecoflex 050 (resulting in a conductive and sensing layer) and one using Ethanol and

[169] see https://softroboticstoolkit.com/resources-for-educators/tsh-sensor
[170] see https://www.instructables.com/Silicone-Devices/

Ecoflex 050 (the actuation layer) which are then combined into sheets electronics. The result is a metamaterial composite that responds to heat through shape change (used in 2D & 3D geometrical configurations) or color change (when used with pigments) or both; while having sensing & tactile capacity.

7.4.2.4. Pneumatic Systems at scale: between façade systems and interior elements

The above design research work explores the design space of soft robotics for environmental data awareness in workplace interiors.

Further research on composite materials to enhance wellbeing and climatic awareness is meaningful. In the case of air quality, research on combining pneumatic actuators with air filtering materials to create adaptive porous walls can be a novel avenue; or pneumatic structures with adaptive openings and heated partitions and to assist with indoor/outdoor air circulation and stack effect.

Finally, research on the impact of scale and spatial arrangement of pneumatic feedback is meaningful, to establish an understanding of how the users of that space interpret and respond to climatic pneumatic feedback. This is the core contribution of the next chapter; addressed through a series of studies with experts and users of the space, through workshops and as a lived-in installation.

7.4.2.5. Pneumatics, swarm robotics and user-customizability

The concept of swarm robotics came across in my work [225,275]. Swarm robotics in architectural interiors currently have very limited applications. The work of Alexandra Ion [164,401] is some of the few examples illustrating the potential of soft structures having a swarm behavior.

Research on user-customizability of pneumatic interiors is also on the rise; LiftTiles [360] is an example of an adaptive floor accommodating different usages. Taking that further, there is space for user-control and customizability to be taken further, towards both physically and digitally customizable pneumatic interior structures.

There is an interesting point of intersection between user interaction, user customizability and swarm robotic behaviour of pneumatic interiors & facades where further research is meaningful.

7.4.3. Next steps

This Chapter (Chapter 7) is concerned with the making of soft robotic interventions with the purpose of using them as climatic displays in the workplace; while the next Chapter (Chapter 8) is concerned with their evaluation. Chapter 8 illustrates the results of a series of qualitative studies facilitated by ActuAir prototype's installation in the workplace with the purpose of evaluating the building occupants' experiences of the intervention.

Chapter 8. Design Evaluation: Understanding Building Occupant's interactions with ActuAir air quality display

8.1. Introduction

8.1.1. Research Context

Design research on the experience and use of large-scale shape-changing displays [112,295,306] within the built environment is a relatively underexplored space, even amongst the Human Building Interaction (HBI) [7,142,332], Adaptive Architecture (AA) [169,329,331] and Soft Robotics (SF) [36,302,305,328,354] research communities. Whilst the design of (soft) robotic skins for environmental control has been possible in architecture for a few decades [189] – and there are several existing prominent examples of pneumatic façade systems that use these kinds of technologies [34,55,116] - there has been very little research on how building occupants actually *experience* such interventions, and even less research on how these kinds of actuated and responsive systems might be effectively used as *physical displays* for the purpose of communicating data to building occupants. With workplace buildings becoming increasingly sensor-rich and amidst climate change pressures, there is growing interest in using *environment* data within buildings for awareness and wellbeing purposes [41,422]. Air Quality (AQ) measures within buildings have received particular attention post-COVID-19, and my own previous research [216] (see Chapters 5,6) has pointed to the desire of building occupants to be more aware of AQ within their workplaces. However, to-date, design research around large shape-changing displays has barely addressed building occupants' experiences of AQ data; a few limited examples such as the 'atmospheric interfaces' work [41,158] help to illustrate the existing research gaps in this space.

8.1.2. Research Questions

While Chapter 7 is concerned with the making of ActuAir, Chapter 8 reports its evaluation by the building occupants through its installation in the workplace.

The key research question driving the prototype's installation and evaluation that this Chapter addresses is:
RQ3: What design interventions in workplace buildings can support data experience for wellbeing?
And more specifically
RQ3b: How do the occupants experience, understand and interpret this feedback?

Responding to this research question, I report on how the building occupants experience ActuAir (see Chapter 7) a novel large, configurable, shape and colour changing display for communicating AQ data to occupants of a smart (workplace) building. The ActuAir system (as described in Chapter 7) is a new kind of modular customizable room divider heavily inspired by biomimetic concepts, which displays AQ data through inflation and LED animations.

Understanding the paucity of evaluations of such interventions I set out to evaluate ActuAir through three exploratory studies during June-August 2022 with 21 participants, all occupants of the building. The three studies included design criteria evaluation workshops with 12 experts; a co-creation workshop with 5 participants focused on concepts of biomimetic feedback; interviews and a survey with 7 participants following a two-week installation of the display *in situ* within the workplace.

Qualitative data from all studies were thematically analyzed; providing insights on how the building occupants experience and interpret the display, this was delivered both in absence of, and with knowledge of, what it actually represents. The results of these studies unpack how the building occupants perceive, interpret and experience the display; their sense-making with regards to AQ data; and what their expectations and aspirations are in terms of configuring and using the display within the workplace.

8.1.3. Research Contributions

This Chapter makes four key contributions to HCI/HBI research: 1) it introduces a novel modular shape and color-changing display technology – ActuAir – designed to communicate within-building climate data; 2) it unpacks building occupants' experiences of interacting with a large shape and color-changing configurable display, presenting particular insights around how different inflation and LED feedback configurations were perceived, interpreted and experienced when communicating AQ data, through both controlled and 'in-the-wild' deployments; 3) based on the findings, it offers design implications and design recommendations for soft robotic (pneumatic), programmable, shape changing and physical displays as awareness interfaces deployed in smart buildings and 4) offers suggestions for future design research (a design agenda) on soft robotics and actuating materials for climatic awareness within the workplace. These contributions to HCI/HBI research, aim to support the design of future smart buildings that wish to employ large-scale soft robotic and shape-changing responsive architectures to engage with their occupants in climatic awareness, and for broader climate considerations and wellbeing purposes.

8.2. Methods

Prototypes illustrate examples of technology in-progress [388], illustrating ideas and concepts of technology to-be [265,297]. Through their evaluation, knowledge about the prototype itself and the potential of the theoretical/technological concepts that it embodies to change the future is generated [388]. In design research in HBI and Adaptive Architecture, prototypes are often deployed to conduct lab experiments [330], case studies and long-term deployments in the wild [57,370], aiming to generate knowledge about the prototype/intervention and human behavior around it. As an example, ExoBuilding [330] illustrates the deployment of a prototype (an interactive tent-like structure) and a series of controlled experiments to observe aspects of human behavior based on biometrics.

The evaluation through deploying a physical prototype is a more generative process than merely a usability evaluation [136]. Many works face limitations with regards to the generalizability of the results [324] outside a controlled context, failing to address the long-term implications of lived-in technology in place [370,421]. In response to such methodological problems, I engaged with different methods in three successive evaluation studies that were led by, assisted by or focused on the prototype's deployment. Fitting within a pragmatist methodology within design research [129], methods were used in a way that fits the purpose while allowing space for critical discussion [136] not predicating the exact set up and content of each study but rather letting it evolve through interactions with participants. This was supported by the prototype itself, which allowed for the customization of its physical arrangement and feedback; which was utilized by the researchers while exploring how the building occupants perceive, experience and interpret it.

8.2.1. The prototype: ActuAir room divider

ActuAir prototype is a shape-changing modular display that physicalizes changes in AQ levels in a sensory-rich workplace. The workplace is an open space hosted in a five-story smart building in a city in the UK; with an extensive grid of environmental and occupancy sensors provided for research purposes. Sensory data is logged publicly via an API, allowing open access to real-time and historical (timeseries) climatic data of different areas in the workplace (and the building). Ethical approval was obtained at Newcastle University, UK to use the data and conduct the studies in the building (which is part of the Newcastle University building complex.

The prototype was built as a response to findings as described in Chapters 4,5,6; which pointed towards physicalizing data that the building collects for awareness and wellbeing purposes [215,216]. The prime purpose of the display is to surface AQ data collected, focusing on - but not limited to - CO2 measurements. A key research aim through prototyping and testing the display was to understand what data is important for AQ experience in the workplace, and how this data could be represented through inflatable and LED feedback to be intuitively perceived and understood by the building occupants when deployed in place. For the purpose of conducting this research, the prototype is highly customizable; to enable to evaluate different physical arrangements and feedback configurations for communicating climatic data with the building occupants of the workplace. Apart from the working prototype, the materials and other in-progress prototypes were openly exhibited in the workplace; showcasing the design and fabrication process, which involved experimentation with different color and shape-changing materials (Figure 105 D).

The final prototype is a customizable, modular actuating barrier providing a physicalization of data in place. It's intended use is to raise awareness on climate – specifically AQ - in the workplace; but this purposefully remains vague in some of the studies to explore how the building occupants understand and use it. The broader research scope of the prototype's deployment as an intervention was to build an understanding of the potential of actuating materials and soft robotics in architecture (inspired by biomimicry) to communicate climatic data; with the view on engaging the building occupants in considering air quality, climate and their wellbeing in the buildings.

A detailed description of the prototype can be found in the previous chapter – Chapter 7, section 7.5.1.

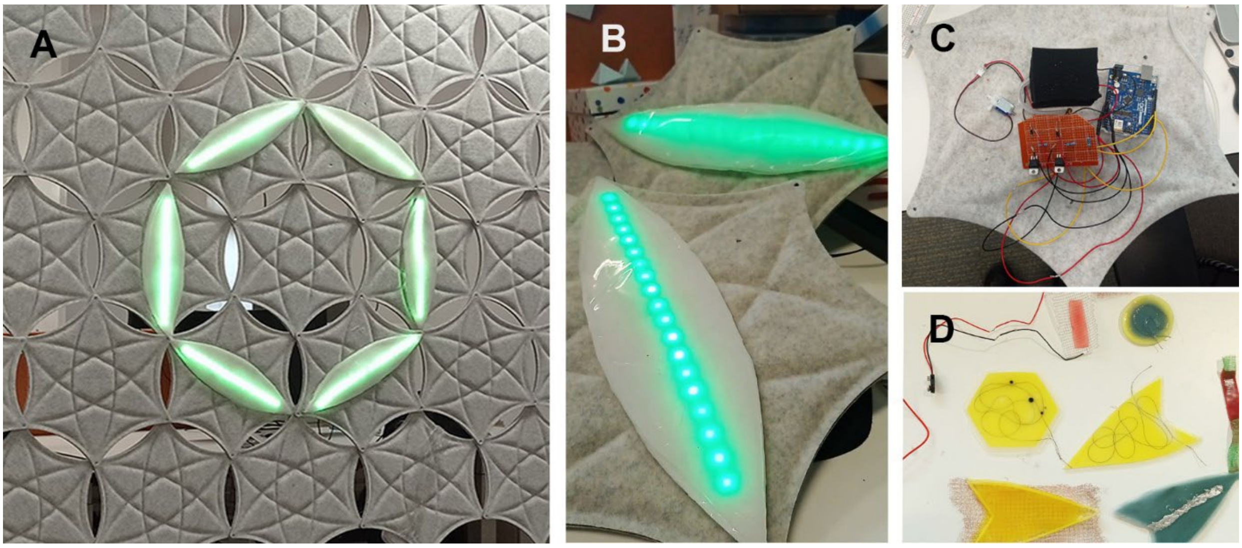

Figure 112: A: the prototype deployed; B: the inflatable pouches with embedded LEDs; C: hardware in the back of each module: a wireless Arduino controlling a foam-sealed air pump and a valve; D: work in progress, experiments with silicone thickness, thermochromic pigments and conductive materials.

8.2.2. Three exploratory prototype-led evaluation studies

Three successive studies took place between June and August 2022 to evaluate the above display. Each study was led-by or facilitated-by the prototype's installation in place; addressing feedback awareness, perception and interpretation by the building occupants as described in detail below. Utilizing the display's configurability and modularity, different physical arrangements and feedback sequences – i.e. shape and color change coordination - were evaluated with participants. The studies overlapped with regards to what aspects of the experience they explored, supporting data triangulation; but they also informed each other in terms of set-up, context and focus, based on key findings as described below. All the materials and the final prototype itself remained publicly displayed in the workplace throughout the duration of all of the studies.

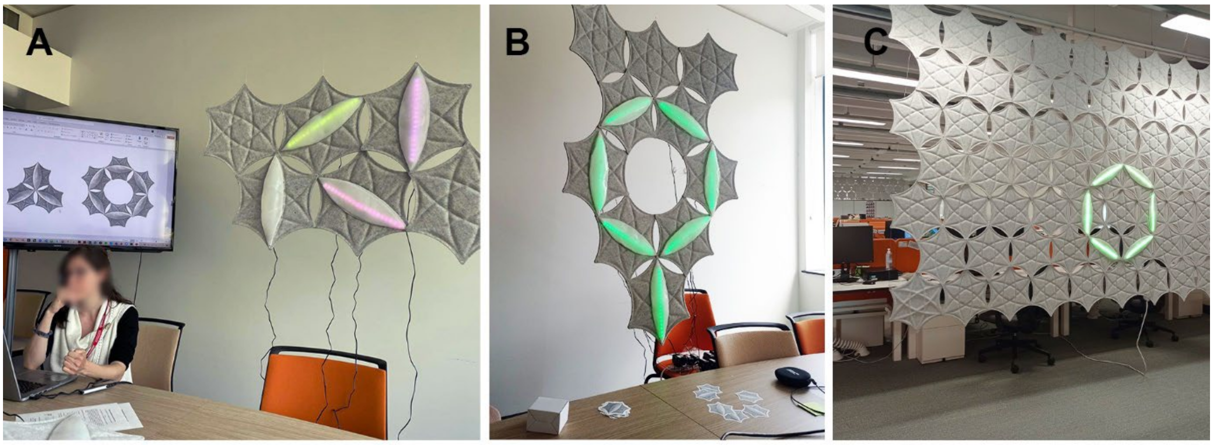

Figure 113: Installations of the prototype to facilitate three evaluation studies; A: Study 01, B: Study 02, C: Study 03. In Study 01 a big screen was used to display a presentation and the control panel. In Study 02, a big screen was installed in the room to display the video-recorded feedback scenarios.

8.3.2.1 Study 01 "ActuAir - Design criteria evaluation workshops" was a series of design criteria workshops led by the prototype's installation in a meeting room (Figure 106 A), aiming to explore the feedback perception of experts and simultaneously occupants of the building in a controlled set up. Nine participants in total – building occupants and design experts - participated in three hybrid workshops (60 minutes in duration) during June 2022. The prototype was installed in a meeting room within the workplace building, showcasing a potential (random) arrangement and feedback functionality. In terms of feedback, both real-time data and historical data were showcased using a non-gradual green-orange-red[175] LED to represent increasing CO2; increase was also accompanied by inflation. Each workshop started with a briefing of what the intervention does – i.e. displays air quality data - and how – i.e. showcasing feedback control; followed by going through specific design evaluation criteria and addressing relevant questions to prompt critical discussion. Criteria included a) Physical aspects of feedback - shape change, color change, noise experience; b) Temporal aspects of feedback – experience of the coordination between light and inflation in each module and between modules; c) Spatial aspects – physical positioning and arrangement; d) Configurability and user control. Real-time modifications were made to feedback, to test participants' ideas. The aim of Study 01 was to unpack the promising elements and existing pitfalls of the display's materialization, and then define the conditions for one or more deployments in the building. Findings on biomimetic feedback metaphors framed the focus and setup of Study 02; and findings on shape-change readability, noise and color-inflation coordination informed the setup of Study 03.

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[175] RGB colors and levels as set in the code for Study 03 set up to favor a more gradual color change. The AQ range represented by each color has shifted to a lower benchmark (i.e. 550ppm), closer to the realistic CO2 measures range in the building (CO2 rarely exceeded 550ppm). These included: Green: [0, 255, 0] for AQ between 400ppm and 420;NeonGreen: [80, 255, 0] for AQ between 420ppm and 440ppm; LightGreen: [160, 255, 0] for AQ between 440ppm and 460ppm; OliveGreen: [160, 165, 0] for AQ between 460ppm and 480ppm; LightOrange: [255, 165, 0] for AQ between 480ppm and 500ppm; DarkOrange:[255, 80, 0] for AQ between 500ppm and 520ppm; Coral:[255, 30, 0] for AQ between 520 and 550ppm; Red: [255, 0, 0] for AQ over 550ppm.

8.3.2.2 Study 02 "Biomimetic Feedback co-creation workshop" was a co-creation workshop facilitated by the prototype's installation in a meeting room during July 2022 (Figure 106 B). The workshop (60 minutes duration) aimed to explore feedback perception and interpretation in a controlled set up. Five participants explored their interpretations of five video-recorded biomimetic feedback configurations using the prototype to provide cues on AQ readings while also experiencing the prototype installed in place; inspired by key findings on biomimetic feedback in Study 01. After an initial showcase of all the videos and without communicating the display's purpose (to physicalize air quality data), the participants were asked high-level questions around what data was represented and how they interpreted the different feedback scenarios. This was followed by a second showcase of each video while communicating that air quality data is displayed; and an in-depth discussion of how each configuration and feedback was interpreted. Finally, the participants were asked to vote for which one appealed to them the most and co-design their own modular configurations using paper templates. The aim of Study 02 was to explore how the shape and color change coordination of different modular arrangements inspired by biomimetic metaphors is interpreted; both in absence of and when knowing that air quality is represented. Findings highlighted the preference of circular modular arrangements, and the association of modules with areas in the buildings and spatialized data streams; which then drove the setup of Study 03.

8.3.2.3 Study 03 "ActuAir - deployment case study" was a longer-term case study deployment of the prototype in a public area in the workplace during August 2022 (Figure 106 C); aiming to explore feedback awareness and experience in-the-wild. Grounded within literature on evaluating lived-in prototypes [265,421]; the intervention was installed in the workplace and was left to operate there for two (2) weeks. The deployment set up was driven by findings of both Study 01 and 02. It included the choice of circular modular arrangement for the deployment (Study 02); the association of each module with different building areas & sensors (Study 02); the gradual green to red color range[176] to represent CO2 increase as it was interpreted intuitively and was preferred over non-gradual color change (Study 01 & 02); the use of inflation when CO2 increases (Study 01 & 02) using noise effectively and with precaution (Study 01); the positioning of the display at an angle to the main working area to make shape-change more readable from multiple viewpoints (Study 01). During the two-week period, the six-module circular arrangement displayed CO2 data from nearby sensors; from the same sensor in week 01, and from the three (3) nearest sensors in week 02 which created

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[176] RGB colors and levels as set in the code for Study 03 set up to favor a more gradual color change. The AQ range represented by each color has shifted to a lower benchmark (i.e. 550ppm), closer to the realistic CO2 measures range in the building (CO2 rarely exceeded 550ppm). These included: Green: [0, 255, 0] for AQ between 400ppm and 420;NeonGreen: [80, 255, 0] for AQ between 420ppm and 440ppm; LightGreen: [160, 255, 0] for AQ between 440ppm and 460ppm; OliveGreen: [160, 165, 0] for AQ between 460ppm and 480ppm; LightOrange: [255, 165, 0] for AQ between 480ppm and 500ppm; DarkOrange:[255, 80, 0] for AQ between 500ppm and 520ppm; Coral:[255, 30, 0] for AQ between 520 and 550ppm; Red: [255, 0, 0] for AQ over 550ppm.

variations on the color change pattern of the modules. During week 01, an information poster next to the prototype informed that it displays data from the building – not explicitly stating that CO2 is displayed - and provided a QR code leading to short online experience questionnaire. The poster was updated during week 02 – informing that it is an air quality display. The actual data sources and zones displayed were not revealed during the duration of the study. Data from seven building occupants were collected through semi-structured interviews conducted in front of the display and through the online survey. The aim of Study 03 was to map aspects of shape and color changing feedback experience– including materiality - in-situ; to unpack if and how the circular modular arrangements are associated with localized and spatialized data streams; and to evaluate if the selected color and shape change (and noise) feedback raises awareness in place – if it is being made aware while working in the lab, if it is distracting, and how it is interpreted with regards to climate (both knowing and in absence of knowing that air quality is displayed).

8.2.3 Participants

Participants (Table 5) were recruited from occupants of a shared workspace based in the office building part of Newcastle University; which is the building that these research activities (i.e. the making of the prototype and the evaluation studies) were conducted. Participants were employees, researchers and students working in the same workplace for varying amounts of time; recruited through internal communication of the studies via email. For all studies I accommodated to post-pandemic work life limitations[177]; targeting to recruit people that were coming to the workplace at the time of the study (as many worked mostly from home). For each study different participants were chosen, to avoid being knowledgeable on what the display does or biases from previous studies. For Study 01 (design criteria), participants were recruited following a convenience sampling method, I invited HCI researchers, designers and software/hardware engineers working in the space, based on their design expertise and availability. They were organised into three groups based on their specialism, for conducting three workshops[178]. For Study 02, a group of students was randomly selected; who used the workspace for a specific amount of time during the studies. For Study 03 (deployment case study), participants were chosen based on how often and how long they were working in the building for; recruiting full-time researchers and employees that work at least three full-time days in the office and did not participate in Study 01. Participants were not incentivized to take part in the studies.

Table 5: The participants: expertise, study number, mode of attendance, how often they work on-site

[177] Study 01 accommodated remote participation although prioritized physical presence due to the nature of the project.
[178] The first group (W01) held primarily software/hardware expertise; the second (W02) primarily design research; and the third (W03) a mix of software & design research.

Participant number	Study & Workshop number	Gender	Expertise	Days per week at work
P01	S01 W03	M	Software design & research	
P02	S01 W03 - remote	M	Software & Hardware design	
P03	S01 W02	M	HCI / User research	
P04	S01 W02	F	Design research	
P05	S01 W02 - remote	F	Design research	
P06	S01 W02	M	Design research	
P07	S01 W01	M	HCI research, hardware design	
P08	S01 W01	M	Software & Hardware development	
P09	S01 W01	M	HCI / User research	
P10	S02	M	N/A	
P11	S02	M	N/A	
P12	S02	M	N/A	
P13	S02	F	N/A	
P14	S02	M	N/A	
P15	S03	M		Full time on site
P16	S03	F		2 days per week
P17	S03	M		2 days per week
P18	S03	M		3 days per week
P19	S03	F		Full time on site
P20	S03	F		Full time on site
P21	S03	F		Full time on site

8.2.4 Data analysis and presentation

All workshops (Study 01 and 02) were video-recorded and transcribed using Otter.ai. In Study 03, interviews were audio recorded and transcribed manually. Transcripts (all together) were qualitatively analyzed using Thematic Analysis [33] resulting in thematic insights on users' perceptions and experiences of the intervention. The analysis produced themes related to physical aspects of feedback – shape change, color change and noise experience; temporal aspects of feedback – experience of coordination between these systems in each module and between modules; spatial aspects – i.e. physical positioning and arrangement in the workplace; configurability and user control. Findings from all studies are presented together clustered under main themes. Raw data is presented (participants' quotes) to support findings; accompanied by the participant's number in brackets (for Study 01, the workshop number is also noted).

8.3. Findings

The following main themes presented below: 4.1. Physical and spatial aspects of feedback perception; 4.2. Biomimicry, materiality and embodiment; 4.3. Feedback repetition, rhythmicity and momentum; 4.4. Data use, interactivity and configurability. Key findings are grouped into Design Implications (DI); which will be further unpacked in Discussion.

8.3.1 Physical and spatial aspects of feedback perception

DI01- Modules' positionality key for shape-change readability. Results from Study 01 and 03 highlighted differences in participants' awareness and perception of shape-change depending on the display's physical positioning. Study 01 illustrated that the observation angle - i.e. observing the display from a fixed front-facing point of observation - can inhibit shape-change perception; "too subtle (P07-W01)"; "not dramatic or extreme enough (P04-W02)"; "...to create an impression and capture attention in distance (P08-W01)". These findings informed the set-up in Study 03 where the display was installed vertically within a main corridor, to be approached and therefore observed mostly at an angle. The fact that the building occupants were able to approach and freely move around it in Study 03 also reduced some of the difficulties with shape-change readability observed in Study 01.

DI02- Utilizing outlines and shadows to enhance shape change. Participants in Study 01 brainstormed ideas to address shape-change readability issues. Some suggested attaching the inflatable pouches to less-rigid components (acting as muscles to bend a surface), or covering them with material features to further enhance outline's shape change; *"soft bendable materials (P07-W01)"; "covering them with soft materials with holes (P03-W02)"; "... with geometrical properties that can create a more visible shape change when inflation or deflation is actuated, changing the visible outline (P08-W01)";* pointing towards using materials with geometrical features that further enhance the shape change occurring during inflation (Figure 107). Adding to this, In Study 01, participants suggested the use of spotlights or sidelights to *"enhance the outline of the inflatables and utilize their shadows as part of the experience (P08-W01)",* creating a more dramatic effect readable from all observation points and at a distance.

DI03- Light defuse and pulse key for inflation perception. Participants in Study 01 & 03 further acknowledged that the embedded LEDs play a key role in enhancing shape-change awareness and perception; found the light defusing effect (as the pouch inflates) intriguing and suggested utilizing this effect further. The coordination of inflation and LED animations was extensively discussed by participants in Study 01 with a view to better supporting inflation awareness and feedback perception; with participants suggesting effects such *as "light pulsating when inflation has reached its maximum (P04-W02)"; or "(the pouches) can stay semi-inflated to diffuse light better (P06-W02)".*

DI04- Light as material In Study 03 participants' observations highlighted experiences of the color change and the aesthetic aspects of inflation and materiality; with *"(inflation) changing light distribution (P15); and even "the color of light changes because of inflation ... I think light becomes brighter when it deflates" (P16).* These findings – i.e. linking shape change and materiality with color distribution and feedback perception – are uniquely to the field of soft robotic shape changing displays; and can open up avenues for exploration of the perception of these parameters (and their coordination) for the purpose of communicating data in various contexts.

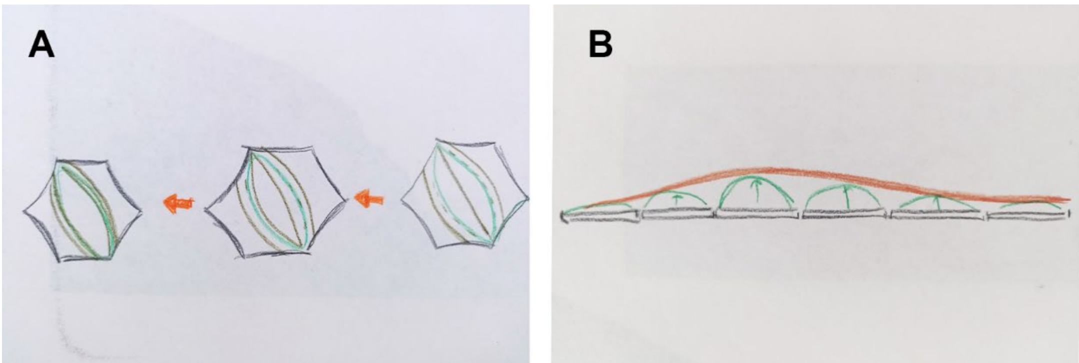

Figure 114: The sketches above illustrate some of the participants' ideas. B: "assemble the pouches on a less-rigid surface; operating as soft muscles to bend the surface (P07)". A: "... vertical placement of surfaces on top of the pouch, which move horizontally when inflated; to make shape change more visible (P08)".

DI05- Circularity and spatial data associations. Results in Studies 02 and 03 illustrated how the modularity of the display (see Figures 108, 109) inspired thoughts of spatialized data representations. Some participants in Study 02 perceived the circular modular arrangement as representing an area in the building, linking the overall shape of the display with a location of data streams; others (Study 02) viewed each module linked to different rooms or room sensors, both in circular and in non-circular arrangements (see Figures 108, 109). These spatial relationships were extended to interpreting feedback variation between modules. When modules were not synchronized, they were perceived as showing different areas in the building (Study 02). With regards to the circular arrangement; *"My interpretation is as every module represents a room and it depicts the air quality in the room over a brief period of time (P11)"; "I think it's different blocks in a building rather than rooms -like block A,B,C etc. and if there is less amount of oxygen in block A, it turns red and simultaneously do the others (P13)".* Intersecting modules (modules on the intersections of two circular arrangements) (see Figure 7 B, C) were perceived as displaying the averages between the sensory readings of two areas.

In the case where one (central) module was behaving differently from the surrounding circular ones, participants interpreted this as the 'average AQ' - i.e. the physical middle point as the data (middle - point) average - or as having different sensitivity to data. *"It's more like the outer ring responds to 70% of CO2 and the inner core responds to 100% of CO2 in the atmosphere. (P12)"; "It might depict the gradual rise in CO2 and say 70-80% of rise in CO2 might change the color of the core. (P14)".* These findings connecting modular display elements to spatial data relationships can be key insights to guide the deployment of such awareness displays in the context of smart buildings.

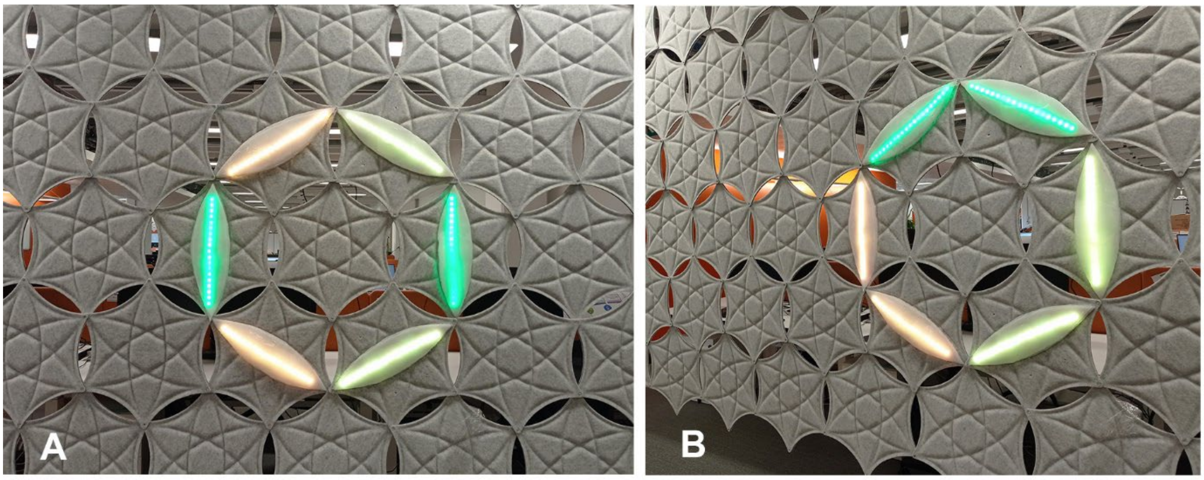

Figure 115: The prototype deployed at a circular arrangement during Study 03. A and B show changes in the LED colors due to changes in CO2 levels and in selected sensors during the 2-week study period.

8.3.2 Biomimicry, materiality and embodiment

Participants in all studies intuitively related to the display of climatic data, based on shape and **DI06- Form and material key for environmental associations.** As the prime aim of the display is to physicalize climatic (AQ) data such as CO2, the participants discussed how well it serves its purpose. Participants in all studies intuitively related to the display of climatic data e.g.*"... it seems it senses temperature from different zones in the building. (P10)"*, based on shape and broad design factors such as color and material properties *'it is green and has leaf-like shapes (P15)'; "it is nice how 'material is making light diffuse... resembling something from the ocean (P15)"; "gluey texture (P16)".* Study 03 illustrates that materiality drove participants to touch the display; many felt it was pleasant or interesting to touch the *'gluey texture (P16)'* hinting towards providing more opportunities for genuinely tangible interactions and tactile feedback to create embodied connections to climate-related data (Figure 109). Across studies, participants expressed views suggesting that the display was evidently and intuitively linked with environmental data, but CO2 was not necessarily an obvious connection *"the design is too abstract to be associated directly with CO2 representations (P04-W02); 'it is too nice to visualize CO2, and it should be more ugly or extreme' (P06-W02).*

DI07- Light and inflation coordination enhances climatic associations. Participants in Study 01, inspired by the prototype's physical properties, saw the coordination of inflation and LEDs (and the adoption of biomimetic metaphors) as a way to better support feedback awareness and intuitive interpretation of the display; and potentially link it better to CO2 data representations. Some participants (Study 01) suggested abandoning use of the 'traffic-light' system (non-gradual green-orange-red LEDs) to represent CO2 levels, in favor of using two-color or one-color representations, gradual transitions between colors, and LED animations to draw attention – e.g. light blinking or pulsating at critical moments. Participants in Study 01 further engaged with biomimicry to support their display and feedback design ideas, relating different feedback scenarios with natural processes; including breathing, the life-cycle of corals and the CO2 accumulation by leaves: *"red turning to pale red and white as air quality worsens, imitating the life-circle of corals (P03-W02)"; "each module represents a leaf accumulating CO2 as it inflates, turning from green to red (P06-W02)"; "light could be 'pulsating' (i.e. fading-in and out at a regular rhythm) to illustrate the rhythm of CO2 concertation, turn red and starting blinking when CO2 reaches a critical level, and then stay red until CO2 decreases (P06-W02)";"the breathing metaphor ... the pace of breathing (LEDs pulsating) changing when CO2 levels change (P05-W02)".* These metaphor concepts inspired the framing of Study 02; they were translated in specific modular arrangements and specific shape & color feedback sequences (Figure 109) which were evaluated in Study 02. Key findings in Study 02 illustrate that light and inflation feedback (and the synchronization of these two systems) through different modular arrangements designed based on biomimetic metaphors that address climate and CO2 accumulation (or the effects of its accumulation on nature), can provide direct cues for intuitive sense-making and interpretation of modular awareness displays; linking the interpretation of such feedback with climatic aspects and climatic deterioration (Figure 109).

DI08-Color drives feedback interpretation. Across studies, LED color was seen as the dominant mechanism to communicate both absolute (AQ measurement) and relative (AQ change) information, as well as rhythm of AQ change *"It's pretty straightforward: Green is good, and red is bad, time to leave the room or open a window (P12)"; "It's green and inflated and turns red and deflates when there is higher than the ideal temperature (P10)".* Inflation acted as complementary mechanism for sense-making directly linked with accumulation in nature (of CO2 or O2) but having a diverse meaning with regards to being positive or negative. *"... inflation increases for representing CO2 levels (P02-W03)"; "There's more oxygen when the prototype inflates since it's green and deflates when there is more CO2 exhibiting red color. (P11)"; "It should probably go the other way around...it would be better if the prototype gets large and makes noise when it goes red to alert the user something is happening (P10)"; "Inflation indicates something positive, whereas shrinking something negative (P15)".* In two-color representations – e.g. the Coral life-cycle in Study 02- participants anchored themselves around red color being 'bad' -e.g. high CO2 (see Figure 109)- which again confirmed the dominance of color in feedback interpretation highlighting the green-to-red color scale as the key element for sense-making; with inflation acting as an accompanying aspect, further enhancing or toning-down the color interpretation.

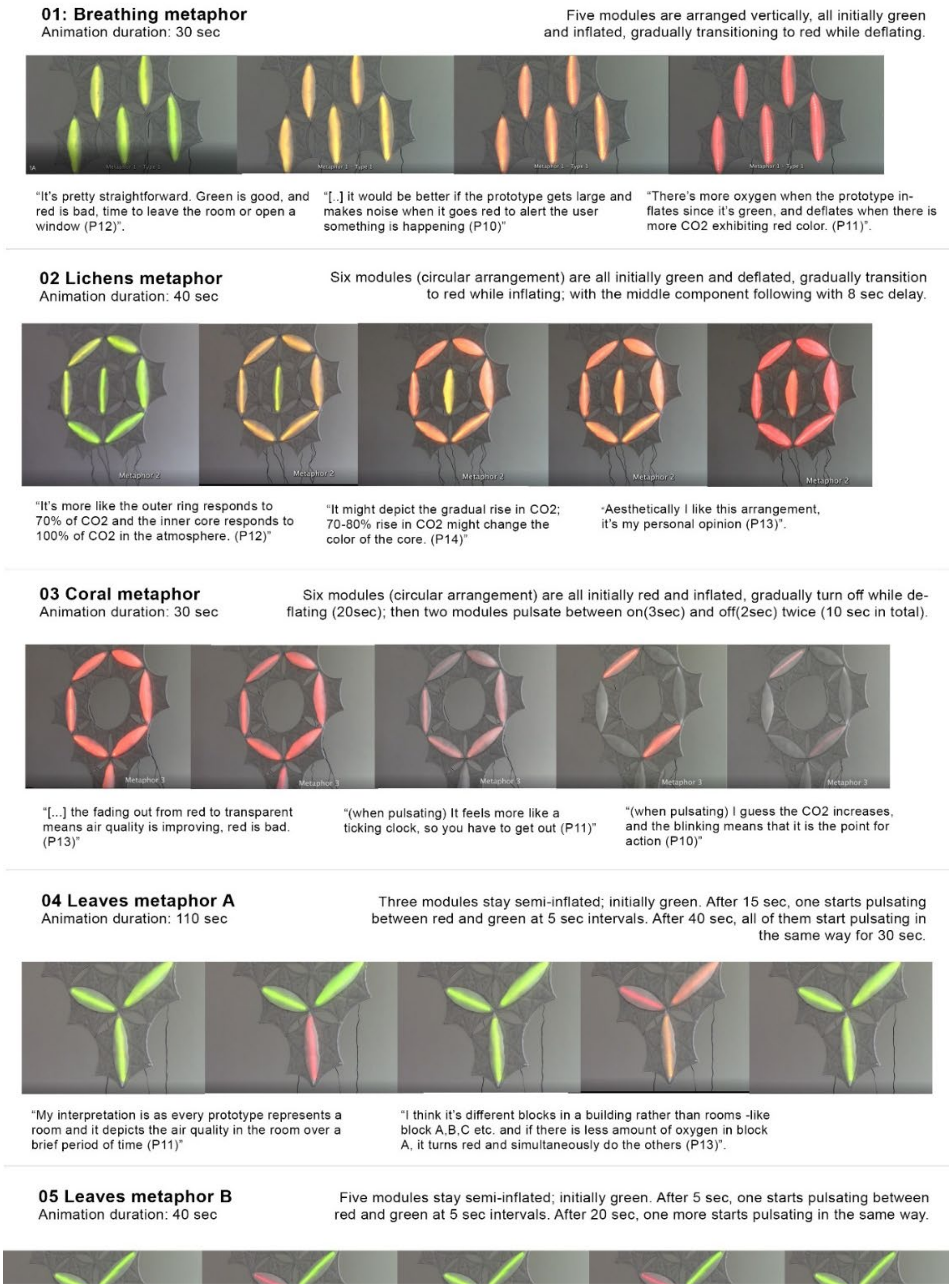

Figure 116: Metaphors explained; 01: Breathing as inflation of lungs - accompanied with color change; 02 Lichens- imitating the growth of lichens through consumption of O2; 03 Coral life-cycle – the death of the coral as CO2 increases; 04 Leaves A- imitating leaves stomata and CO2 accumulation; 05 Leaves B – imitating leaves life cycle. Pulsating means gradual light transition at a fast rate (<5sec). LED color scale used was limited in colors ranging between green and red, as it was easier to interpret. Participants were exposed to the feedback sequences without knowing what data is displayed, and what is the biomimetic metaphor that inspired it.

8.3.3 Feedback Repetition, Rhythmicity and Momentum

DI09-Rhythm of feedback important for awareness. The tensions between feedback repetition, rhythmicity and momentum were apparent in participants discussions (Study 01). The appropriate coordination of LEDs and inflation was framed both in the context of creating momentum when significant change in AQ levels takes place; as well as in the context of creating a sense of pacing and rhythm in the display's operation. Participants in Study 01 suggested normalizing feedback intervals – mostly referring to LED blinking - to create the feeling of time passing accompanied with specific points of momentum. *'The modules functioning as digital digits (P01-W03)' if arranged appropriately; 'the circular arrangement of the modules is imitating an analogue clock (P02-W03)'; "(at a circular arrangement) a repeated LED blinking at even intervals (like a clock) can draw the attention to specific moments; for instance, when the hour has passed and a new reading is available, or when there is a significant CO2 change" (P02-W03).*

DI10-Noise as feedback at key moments. Noise (byproduct of inflation) was seen with mixed feelings by participants in all studies*. "I'm not sure if the prototype gives out so much sound or it's just the video, but it'll be really disturbing if it's the prototype. (P10)".* Participants in Study 01 and Study 02 suggested that noise can be an essential interesting feedback parameter to be used with caution *"Do you think that people will be aware of it by just seeing the colors? (P14)"* implying that its' noise is essential to draw attention; *"Since you can't avoid noise, use it as part of the feedback system, drawing attention when it is needed (P09-W01)"; "(about noise) probably draws attention to the change in the light. (P11)"*. These findings further pointed towards using inflation for CO_2 increase and informed the set up in Study 03. Inflation noise became particularly annoying when displaying the time-series animations during Study 01, which discouraged further discussion of displaying historical data during deployment Study 03.

DI11- Speed of light animation linked to urgency. LED light animations with varying speed, repetition and color transitions were heavily suggested as ways to create rhythm and momentum in the display (Study 01); which were then materialized and evaluated in Study 02. Results from Study 02 illustrate that these variables – e.g. speed of color transition, the color range of LED animations, and repetition - are key to feedback interpretation. A gradual non-repeating green-to-red transition at a speed ~30s created a clear perception of slow deterioration; whereas the same animation at the speed <5s and in repetition created a sense of urgency *"It feels more like a ticking clock, so you have to get out (P11)"* (Figure 109).

DI12- Feedback expectation impacts attention. The design dimensions of feedback rhythmicity, predictability and variation were not easy to navigate in the wild. It became apparent that observations from a controlled set-up do not necessarily apply for in-the-wild deployments. For instance, traffic-light color range and non-gradual color change were seen as limiting in Study 01; with participants expressing that gradual color change could communicate better, and that traffic light color range is over-used. On the contrary, the idea of a traffic-light system was treated positively in Studies 02 and 03 as it was easy to interpret and predict *"I expected it to turn red at some point (P21)'*; while gradual color change was not perceived on time from most participants in Study 03 *"Did it really change since last time? (P21)"; "It's always looked green since I've seen it. (P17)"; "Was it always yellow on some sides? (P19)"*(Figure 110).

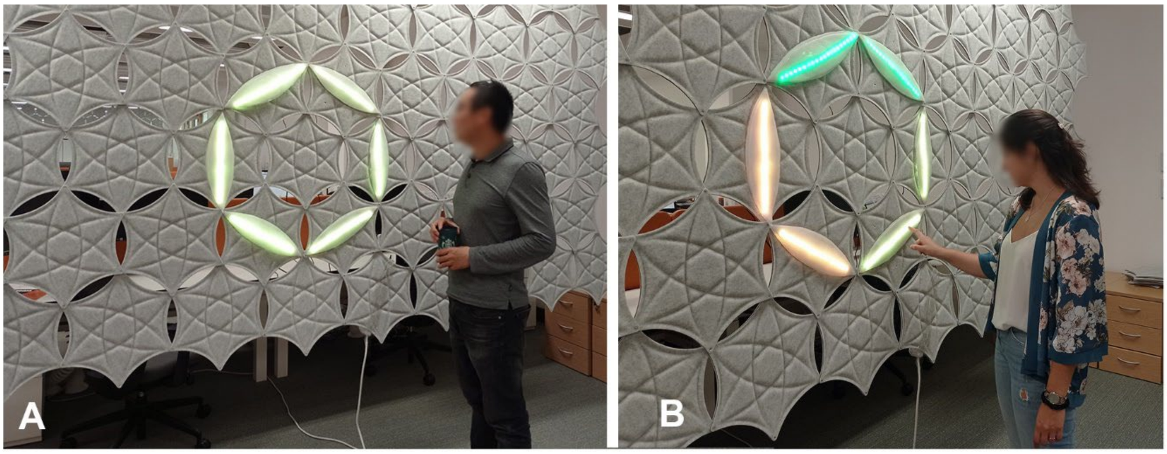

Figure 117: A: short interview with P15, first week of Study 03. P15 thought that the display measures something about the environment or the weather because *"it is green and has* leaf-like shapes ... It also *resembles something from the ocean (P15)".* P15 found inflation interesting with regards to changing the ways the light is diffused; "the way the shape change impacts light distribution is very nice (P15)". P15 assumed that inflation communicates information about how the environment changes, "inflation indicates something positive, whereas shrinking something negative (P15)". B: short interview with P16, second week of Study 03. P16 enjoyed touching the display0 *"the feeling of the gluy texture (P16)"*– hinting towards tangible feedback. *"green is good, and that the display might turn red at some point. I find the display pleasant, blending nicely with the space, visually integrated and non-disturbing ... Does light become brighter? (observed during deflation) (P16)".* P16 thought the display also captures occupancy, and thought it could be a measure relevant to AQ. P16 could not make out which areas/spaces in the building are represented; and suggested that more information should be provided to make it clear.

8.3.4 Data use, interactivity and configurability

Participants expressed the view that the display can be successfully used for displaying diverse data sources in different building locations (or regardless of the building location); as it allows flexibility on how it is used, and it blends well in space *"the design is successful because it has a clear how –what it does, its functionality and functional properties – but an abstract what (it is for), allowing flexibility in its use participants to use it in different ways (P05-W02)'; "It blends nicely with the space, visually integrated and non-disturbing (P16)".*

DI13-Spatial context influences data use. Results in Studies 01 and 02 show that the display's location in the workplace created different expectations in terms of data used and feedback configurations; as well as different speculative reactions and behaviors from the side of the building occupants *"(modules with) the traffic light system can be meaningful outside office spaces; they can notify you if the CO2 is too much (in the room), and you can choose to open the window or go somewhere else (P01-W03)";* or in the meeting rooms, *"It will be* *interesting to see what people will do during the meeting if AQ deteriorates, if they open a window or do a break (P08-W03)".* In Study 02, participants highlighted that, when installed at a central location in a circular arrangement, they expected the display to function as a display of climatic data averages of the main building blocks*" (at a central location) each module represents each block in the building complex. ... The core module in the center is for the whole building complex by itself, or the average of all the (building) blocks in one prototype, hence it's placed in the center (P13)";" This one is like 3 overlapping circles representing each block in our university. So the overlapping modules (the ones that belong to multiple circles) could be the average of the few blocks combined (P10)."*

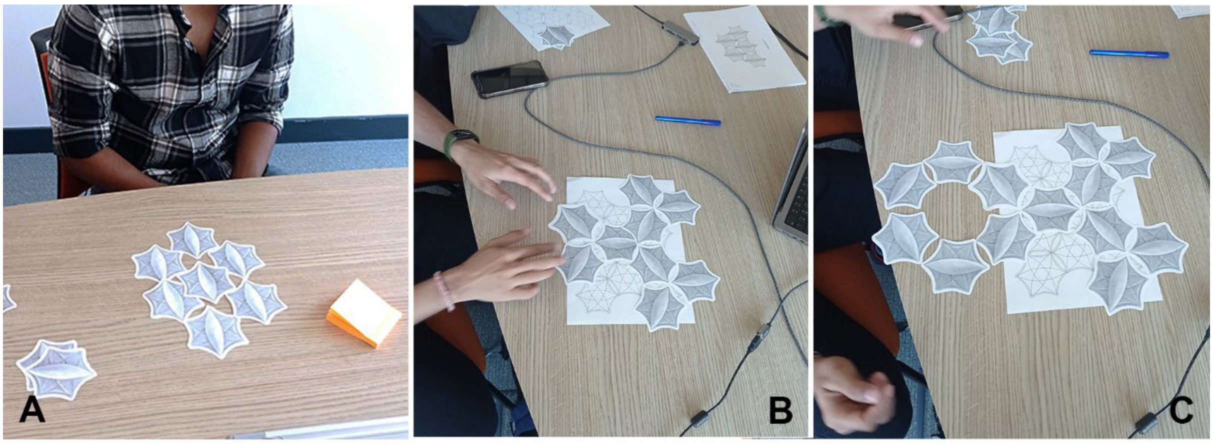

Figure 118: Participants creating display configurations during Study 02; linking modules' arrangements with spatial data & building locations. A*: "This is something similar to the arrangements shown on the video, but it focuses on just one building and different zones in the building (P12)".* B: *"This one is like 3 overlapping circles representing each block in the building. So the overlapping prototypes could be the average of the few blocks combined (P10)."* C*: "I've placed the prototypes in a circular pattern and each prototype represents each block in the building complex. For example, if there is less O2 levels in this building, this will turn red. The core or the prototype in the center is for the whole building complex by itself, or the average of all the (building) blocks in one prototype, hence it's placed in the center (P13)".*

DI14-Feedback tailoring based on occupancy/ proximity data. Beyond AQ and climate data, there were some ideas around integrating different data-sources, including for human activity. *"I felt like it will be based on movement, like with motion sensors ... maybe you have some sensors which brighten up (the display) the more you go closer and dull out the more you go farther (P11)"; "I thought the display also captures occupancy, as a measure relevant to air quality (P16)"; I wonder if it is just building sensors or local sensors too? I don't know, but does it know if people are nearby or even looking at it (P18)".* These ideas can be interpreted as bringing more variation, gamification, and interactivity (and potentially unpredictability) to the feedback from the display; as well as strengthening human – data interactions. It was suggested that motion and occupancy sensors could be used to also control the overall powering of the intervention; and participants also discussed their concerns around energy consumption. *"Out of necessity it uses electricity! (P18)"*

DI15-Extending modularity/plug n' play. A further line of thought around strengthening user engagement included enhancing the existing customizability of the display, designing tools to allow configuration and manipulation by building occupants. The existing modules are easy to move and reassemble in different locations in the building; participants in Study 01 suggested mobile-based interaction could provide incentives for people to actively use the modules and further configure the feedback as they see value. Some highlighted the ability to able to select data sources (Study 01 and 02) – different data sources from different building locations, and potentially their averages (Study 02). *"mobile interaction could be encouraged to select data streams and appropriate feedback features of the display – e.g. light color, intensity, duration (P02-W03)";* the design of a tool that *"allows to visualize your own feedback patterns supporting the drag-n-drop of shapes, modify the feedback (i.e. inflation, light animations) and deploy it in the physical installation (P01-W03)".* Differences in perception of what data is important to represent AQ were highlighted – some referring to CO2 and some to O2. This also suggests potential future value in user customizability of data sources.

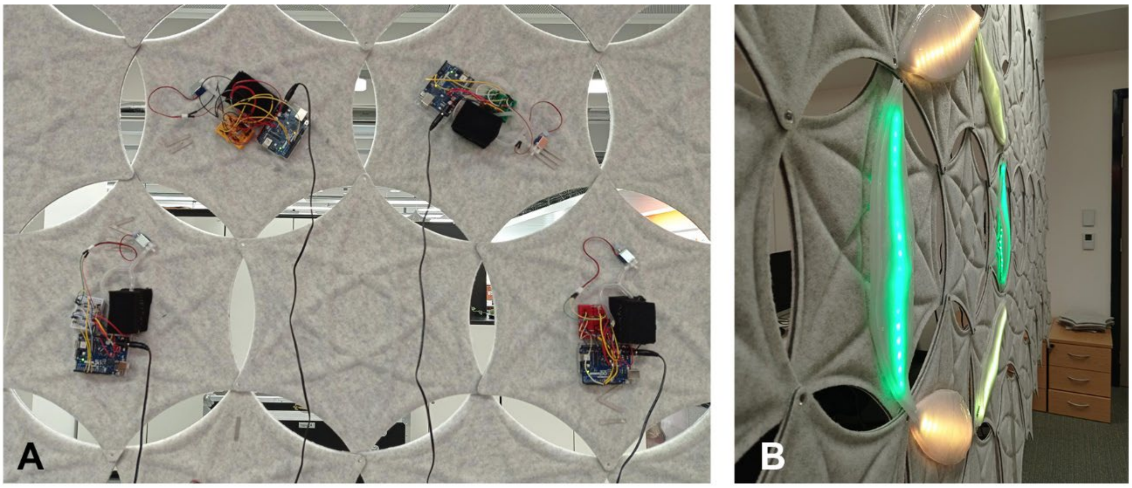

Figure 119: *Looking on the side and at the back of the installation (Study 03). Hardware was purposefully left exposed; contrasting the smooth, bioinspired front face of the module. "Out of necessity it uses electricity! The dangling cable and all the other tech mounted on the reverse is maybe very slightly "disturbing", but reminds us the data is similarly collected by connected tech elsewhere, so I think seeing both sides is good. I am tempted to look more closely at the back (P18)".*

8.4. Discussion

The three prototype-led evaluation studies have contributed key findings concerning occupants' experiences of a large-scale shape- and color-changing display (RQ); a modular customizable room divider inspired by biomimicry operating through soft robotic principles, with the purpose of communicating climatic data (AQ) in a sensory-rich workplace. These findings highlight the building occupants' perception, interpretation and embodied experience of the physical display (RQ) and climatic data in place; and their perceptions of its meaningful use in the workplace. Focusing on evaluating diverse modular arrangements and inflation and LED light coordination scenarios – also framed under biomimetic metaphors – findings in both controlled studies (Studies 01 and 02) and in-the-wild (Study 03) are discussed below as design implications **(DI)** and opportunities for future research.

Table 6 Design Implications (DI), Design Recommendations (DR) and relevant application

Design Implications	Design Recommendations	Type of display
DI01- Modules' positionality key for shape change readability	Allow opportunities to dynamically alter the rotation and position of modules, to allow a dynamic observation angle. This is particularly important for non-rigid pneumatics.	Modular Shape Changing, Pneumatics
DI02- Utilizing outlines and shadows to enhance shape change.	Use pneumatic muscles combined with rigid materials to create stronger outline shape changes; and utilize shadows to further enhance the effect.	Shape Changing
DI03- Light defuse and pulse key for inflation perception	Recommend an increasing light intensity (linearly or in intervals) to support the readability of inflation.	Shape Changing
DI04- Light as material	Integrate LEDs into materials to allow varying light diffuse effects; explore use of light-emitting materials.	Pneumatics
DI05- Circularity and spatial data associations	Circular modular arrangements were favored and associated with 'areas' in the building.	Modular Shape Changing, Context Dependent
DI06- Form and material key for environmental associations	Biological inspiration in choice of materials and forms is recommended to produce environmental associations; extended to use of biomaterials.	Modular Shape Changing, Pneumatics
DI07- Light and inflation coordination enhances climatic associations	Use of bio-inspired animated LEDs together with inflation to enhance climate associations; swarm behavior pointed to data changes in different rooms/areas.	Modular Shape Changing, Pneumatics
DI08- Color drives feedback interpretation.	Recommend green-to-red scale as it is intuitively understood and supports the interpretability of pneumatic shape change.	Shape Changing
DI09-The rhythm of feedback important for awareness	Animations too slow (>30s) were not perceived in the deployment case study.	Broader Physical
DI10-Noise as feedback at key moments	Noise use is not distracting in big public areas, recommended to draw attention.	Shape Changing, Pneumatics,
DI11- Speed of light animation linked to urgency	Light pulsing (gradual change from no color to color at < 5s intervals) repeatedly at key moments drives attention, if below <3s is interpreted as urgent.	Pneumatics
DI12- Feedback expectation impacts attention	Confirming expectations of color changing (e.g. turning red) can be key in maintaining interest on the display.	Broader Physical
DI13-Spatial context influences data use	Recommend providing customizable/programmable context-dependent feedback scenarios.	Broader Physical
DI14-Feedback tailoring based on occupancy/ proximity data	Recommend integrating proximity data for more 'personal' feedback, and occupancy data for energy saving.	Broader Physical
DI15-Extending modularity/plug n' play	Recommend modularity extended on plug n' play tools for digitally customizing feedback.	Modular shape changing

8.4.1 Design implications for large-scale shape and color changing displays: Light, materiality and noise

Results (Study 01 & Study 02) highlighted the importance of coordinating inflation and LEDs, utilizing LED animations to a) to support and further enhance shape change perception **(DI03)** - e.g. in quotes on pouches staying semi-inflated (for diffusing light) and using light pulsating to enhance inflation (P06-W02), the use of spotlights to utilize inflation shadow outlines (P08-

W01), b) create momentum and draw attention to specific moments **(DI03, DI11)**– e.g. light pulsating to enhance maximum inflation perception (P04-W02) and c) create a visual rhythm based on the temporal dimension of climatic data **(DI09)**-e.g. light pulsating in regular intervals to highlight time passing (P02-W03)**.** A fourth aspect was noise, discussed in the context of creating momentum on specific moments and supporting the visual experience of shape change with auditory feedback **(DI10)**(P09-W01). The above aspects (which are further unpacked below) could be framed as key design dimensions for designing with light and inflation for large-scale, modular and non-modular, shape- and color- changing displays; also extendable beyond climatic data representations.

Results from Study 01 highlighted the potential for shape changing materials to successfully provide abstract – yet intuitively understood - visual cues for interpreting state and state change in climatic (and other) data streams; when supported with appropriate lighting **(DI02).** Participants (Study 01) referred to using ambient light to enhance shape change awareness (or to create the illusion of it) suggesting the use of spotlights; utilizing the produced shadows of the shape outlines as part of the feedback strategy (Study 01). Shadows are heavily unexplored as a feedback strategy in HBI/HCI research; illustrating avenues for further design exploration. One of the very few examples is Shutters [71], where natural/ambient light is used to produce shadow projections to communicate visualizations driven by shape changing SMA wires; illustrating gaps and emerging opportunities for design research. Results (Study 01) highlight the importance of feedback at-scale in the buildings' public spaces (Study 01, 02, 03) whilst remaining non-disruptive; which further supports the utilization of ambient light and shadow as part of climate feedback, as it is passive, calm and deployable at scale within the buildings **(DI02).**

Participants' suggestions of geometrical properties to further enhance shape-changing feedback point towards the emerging space of inflatable auxetics [58,278,407] and programmable metamaterials [164,165,401] and their potential application in large-scale displays **(DI01).** The work of Alexandra Ion [164,165,401] extends to exploring programmable, passively-changing geometrical structures and the geometry-enabled swarm behavior of artifacts; see for instance passively reconfigurable shape changing materials [340]; DIY pneumatic metamaterials [77] and modular structures [165]. Such examples have interesting potential for modular user-configurable physical displays; acting as potential output configurations for diverse climatic data sources in buildings **(DI01).**

Although LED color was the driver of sense-making amongst participants; it was seen as inseparable from the inflation and the material dimensions of the display **(DI04).** The employment of LED light has many manifestations in HBI and soft robotics literature; but often not discussed in the context of materiality **(DI04).** Results illustrated that materiality enhanced the perception of light (e.g. P15, Study 03); in Study 03, light obtained a 'material' dimension itself – e.g. P16 notes the illusion of LED color changing due to materiality and inflation. Materiality and light diffuse are intertwined in architectural design, but very seldomly addressed in the context of public displays (see transparency-changing glass for instance [19,406]). Li-Lo displays [336], is one of the limited works which unpack ambient light use and diffuse aesthetics through a series of material displays and projections in-place; highlighting more potential gaps for understanding the experience of light diffuse as feedback for climate and AQ change **(DI06).** These results point towards research on material light and color emitting feedback strategies; examples include the use of thermochromics [60]; as well as light-emitting biomaterials – see the use of cyanobacteria [132] or algae [63] in building materials. Both research avenues have interesting complexities with regards to creating programmable composite / biomaterials for climatic feedback purposes.

Noise when inflation is actuated is a novel aspect of pneumatic systems, usually treated as a problem to eliminate and very rarely as a feedback strategy – see projects such as PITAS [60], an attempt of engineering a pneumatic metamaterial that actuates without noise, and FlowIO soft robotics platform [339] which supports a portable approach for pneumatics claiming to limiting noise **(DI10)**. My findings suggest that there might be opportunities to utilize noise (with caution) for large-scale public displays as part of the feedback strategy. Findings in Study 03 suggest that, in public open-space setting, inflation noise is almost essential to attract attention to specific moments of AQ change; with participants expressing limited concerns about being distracted by the noise. Noise use should therefore be context specific - i.e. might be unnecessary and distracting in a meeting room where there is close visual proximity to the display, and essential to draw attention in specific moments when installed at a public spot. Summarizing, large scale pneumatic displays should subsequently allow a level of programmability for utilizing noise depending on the context of deployment **(DI10)**.

8.4.2 Modular biomimetic feedback for climatic awareness, wellbeing and sustainability

Results (Study 01, Study 02) highlighted that when designing modular shape and color changing feedback, biomimicry can have a direct impact on how intuitively this feedback is perceived and whether it is linked with climatic (and AQ) data **(DI07).** The imitation of natural processes related with CO2 accumulation (e.g. breathing or leaves' CO2 accumulation) or the impact of CO2 accumulation in nature (e.g. the death of corals and the expansion of lichens) was translated through modular arrangements and shape and color change sequences in Study 02, informed by Study 01 findings. Study 02 results show how the above biomimetic metaphors translated in modularized inflation and color feedback were intuitively linked with aspects of deteriorating climate (see quotes in Figure 109).

Modularity expanded the possibility of the existing shape and color changing system to obtain different forms at scale in the buildings [166,272,360]; and generate different dynamic behaviors between modules or groups of modules (see Figure 5, the Leaves metaphor A & B for instance) while still behaving together as a whole (see Figure 5, the Lichens metaphor); which can be framed as swarm behavior [333]. Swarm behavior – i.e. collective motion of independent entities – enabled by modular soft robotics is an aspect of biomimetic design with some applications in kinetic architecture – see Ned Kahn's wind façade[179] - rarely explored in HCI/HBI research [225,275,333]; which can have interesting implications on the development and interpretation of modular, soft robotic displays at large scale [272,360,408]. In this work, different modular arrangements were presented in Study 02; with modules obtaining different

[179] https://nedkahn.com/portfolio/wind-veil and https://nedkahn.com/portfolio/wind-arbor

inflation and color change sequences either individually or as groups (see Figure 5) as an attempt to imitate different aspects of natural organisms **(DI06, DI07)**. Beyond associations with climatic aspects such as deteriorating climate, participants in Study 02 perceived different modular arrangements in direct association with the spatial location of data streams and through to be representing spaces/building areas and the climate data readings from them– something like a physical data map of the building areas. Participants in Study 02 particularly pointed to the circular 6-module arrangement as the most appealing, associating the circularity with the representation of an 'area' in the building; with some replicating circular arrangements to visualize intersecting areas in the buildings during the co-creation activity. Given the number of modules fabricated and used in this study is limited; future work can explore further the installation of different biomimetic feedback arrangements of modular soft robotics at scale, as well as how building occupants perceive them and see value in using them in-situ.

The display was described as aesthetically pleasing (in all studies) and that it provided distinct visual cues to interpret climatic change and climatic levels. The association with specific biomimetic metaphors was picked up by participants in Study 03, when participants suggested that the display shows environmental data based on its 'leaf -like shapes (P15)'; also 'resembling something from the ocean (P15)'. These results from Study 03 showed that, beyond modular assembly and inflation and color change coordination, primary aspects contributing to the climatic interpretation of the display were (as intended) the overall form factors of each module and their materiality **(DI06)**; with some expressing that it was interesting to touch- 'a gluey texture (P16)'- highlighting the possibility of embodied and haptic experience of feedback. Expanding on these findings, materiality could be further explored in the context of designing for climatic data displays, through further research in (material) haptic and embodied experiences; and conceptually, transitioning from nature imitation to nature connectedness (biophilic feedback). Building on relevant literature on architecture and embodied cognition [282,348,359]; material-driven feedback can extend to further imitate bodily reactions and further engage embodied experience of climatic data; for instance, material feedback that imitates sweat [319,399] or broadly skin – see soft robotic skin textures [46,106] - and its responses to the environment [79]. Using such material feedback could also foster climate-sensitive behavior in the buildings [149] – i.e. climate awareness and opportunities to rethink human-climate relationships.

Building on relevant research on biophilic design; experiencing nature can stimulate conservationist attitudes towards the natural environment [180,225,424]; fostering climate awareness and sensitivity on how human actions impact the environment and climate [225]. Along these lines, participants already highlighted concerns over the installation's energy use; questioning why it should be always on (Study 03) **(DI14)**. Responding to participants' energy concerns, reducing overall energy use of the display falls within emerging visual pollution [115] and sustainability concerns driven by current climate pressures. Bio-material research can support the reduction of LED use in the built environment, replacing them with naturally occurring light feedback [269]. Beyond LEDs, pneumatic action – and broadly - shape change also requires energy; with solutions such as PITAS [60] illustrating early potential of composite materials – e.g. conductive silicone- to provide shape and light change with less electricity

while eliminating noise; yet the challenge of zero energy use and self-powered displays remains open. Materials used in passive climatic skins [189] have unexplored potentials in design research for building interiors and physical displays; for the purpose of both reducing energy use and further support biophilia in the workplace. Types of energy-passive climate-actuated materials include thermobimetals (materials responding to heat) [358] and hygromorphic (materials responding to humidity increase) [309,402] require significant amounts of environmental heat or humidity to actuate and currently have limited interior applications. Contemporary advances in biomaterials for architecture - see research by HBBE[180] for instance– open the space for using biology to produce electricity [327]; or engineer materials to respond to or capture CO_2 [17,72,151,286,424]. Such examples can push the frontiers of color and shape change in soft robotics, utilizing biochemical reactions with CO_2 to improve AQ, self-power and provide a naturally occurring feedback [269] – see for instance the work of Goodchild-Michelman [132].
Summarizing, the above results suggest that biomimicry is a meaningful strategy when designing for physical climate-awareness displays; and its success depends on primarily form and material factors; and secondarily on shape and color change coordination. Modularity plays an important role on enabling dynamic visual arrangements and feedback sequences at scale - providing with cues towards spatiotemporal data relationships – with the potentials of swarm behavior of elements to communicate meaning remaining relatively unexplored. Design research on actuating biomaterial feedback is an emerging space for climatic displays; that can potentially support both sustainability and climate regulation while nurturing climate-awareness in the buildings.

8.4.3 Engineering feedback in-place: reflections on architecture-as-display and behavior in context

Findings on how successful different shape and light feedback was in terms of being brought to the occupants' attention and awareness, are discussed in the context of Studies 01 and 02 (controlled installation) and Study 03 (deployment in-the-wild). Although successful in the controlled set up with no distractions (Study 02), green-to-red LED animations did not engage building occupants' peripheral awareness in the wild (Study 03). Unpacking the neuroscience of feedback; timing and priming – to expect feedback to change and therefore anticipate it - within a relevant behavior context [150,359], impacts feedback awareness in place. Seeing the green to red color range, participants were primed to expect a specific color change to red when seeing green, assuming deterioration **(DI08, DI12).** As AQ did not drop significantly during the first days of the deployment maintaining the color change within neighboring color tones (Study 03), results showed participants' attention to the display decreased over time. The request to highlight the perception of time passing through regular feedback intervals **(DI09**)– some referred to a clock ticking (results in Study 01, 02)- highlights the need of rhythmicity in peripheral interventions, which then can attract attention when it changes - becoming fast (sense of urgency, Study 02) or static.

[180] See research by HBBE http://bbe.ac.uk/the-living-room/ and Living Architecture Systems group https://livingarchitecturesystems.com/

With regards to feedback configurations to drive occupants' engagement in the long run, there were no straightforward answers to the problem of 'too repetitive' and 'too unpredictable'. Some participants envisioned the potential of integrating human activity data to the display's function **(DI14)**, creating a more human-responsive feedback. For instance, using proximity and occupancy sensors to animate it around people's movements in the building; creating further associations between building occupants and their contribution to the room's CO2 footprint. Reflecting on relevant research on feedback and embodied cognition [282] which supports the idea that the visual rhythm of the environment can affect body motion (e.g., walking pace), animated CO2 feedback that synchronizes with the pace of people passing by could provide a more 'personal' view of CO2 contributions, a more embodied feel of its change. Feedback configurations that establish relationships between the pace of light/inflation animations and pace of walking of people approaching or passing by could significantly enhance engagement with the display and hopefully create a deeper individual and collective connection to climate within the building. Finally, proximity sensors respond to quotes over reducing energy use of the installation; since it can be activated only when (enough) people are around – providing further links between the amount of people in the building and CO2 levels.

There were associations between the display's configuration and building spaces and localized building data (the CO2 data footprint of indoor building areas) – e.g. participants in Study 02 interpreted the circular arrangement as different building rooms or blocks **(DI05).** In the case where one (central) module was behaving differently from the rest, participants interpreted this as the 'average' or 'middle point' (both physically, spatially and digitally). These perceptions of spatial-data analogies – e.g. the circular arrangement as a physical area; the middle module as the data (middle - point) average - highlight opportunities to further engage with exploring relationships between the display's modular arrangements and spatial / data representations; to further investigate building occupants' spatial sense making and provide cues to perceive where data comes from.

Across the studies, participants shared interpretations of what the display does and shaped a collaborative understanding of its feedback and use through iterative discussions. Spatial behavior context further informed occupants' expectations around the display's function and use in place [39], illustrated when discussing how it can be used in different rooms/areas **(DI13).** For instance, the traffic light system was suggested if using the display in and outside meeting rooms; circular arrangement were favored in public areas to represent CO2 levels in building blocks or rooms. These results contribute to existing literature on modular, DIY and open-source architecture as a collaborative instrument [12,18], highlighting the importance of designing with configurability and modularity in mind, when thinking of large-scale physical climatic displays and providing tools to enable occupants' control when shaping collective climatic data representations and use **(DI15)**; creating the basis for rethinking human-climate relationships through data with the prospect of cultivating climate-sensitive behaviors– i.e. prompting building occupants to think how their own behaviors and actions relate to climate, and potentiall aspects of their wellbeing.

8.4.4 Summary: Opening the design space for soft robotics for biomimetic architecture-as-display in climate change

Through mapping building occupants' experiences of a modular soft-robotic shape and color changing display of climatic (AQ) data in a smart workplace building; we have brought to the fore several design implications (DI) relevant to the application of soft robotics in that context, also extended to the design and deployment of modular (5.2), shape-changing (5.1) and broadly physical displays (5.3.). I contribute to HBI [143] research through opening the design space of modular soft robotics for large physical displays for climate awareness; presenting existing opportunities and challenges for the deployment of such interventions in smart office buildings. Building upon relevant work on biomimicry and biophilic design [180,424] and large-scale soft robotics / actuating materials [328,371] ; but here with a specific focus on lived-in office buildings and modular interventions for climatic awareness, there are several areas of future work which could be fruitfully explored concerning broadly large scale soft robotic displays (see 1-5 below) and particularly modular displays (see 6-7 below):

- Further research on actuating materials in office buildings to support embodied climate awareness through biomimetic haptic and tangible feedback; for instance, soft robotic skin textures [79,160,399] that imitate bodily responses to climate (e.g. sweat).
- Further research in biomimetic and biophilic design for physical (architectural) displays, including bio-materials for capturing CO2 [17,132,309,327] - for instance cyanobacteria [132]or algae[72,151,269]– with a focus on nature-derived light and color feedback.
- Self-powered or low-energy physical climatic displays [327,417]; focusing on bio-materials and mechanisms to drive energy saving.
- Feedback to support awareness on collective and individual climate behavior; linking the display's operation with data on human activity in the building; including opening of the windows, occupancy levels etc.; and the individual and collective contribution to CO2.
- Research on further utilizing noise in pneumatic systems as part of feedback strategy – instead of suppressing it.
- Further research on swarm behavior and modular feedback systems to support further spatialized understanding of climatic data.
- Interfaces for user control of modular displays; including modular robotic interfaces; that incorporate different types of feedback customization and data sources selection through mobile and tangible interaction.

Through these various proposed strands of research agenda – a potential new research landscape emerges focusing on biomimetic and biophilic feedback and actuating materials/soft robotics to communicate climatic data. There is much potential for developing new, engaging and ultimately occupant-centered data-interactions to foster climatic awareness; with the scope of creating opportunities to re-consider human-climate relationships within the built environment, and hopefully this work helps to scaffold future work in this area.

8.5. Limitations

This work has limitations with regards to the prototype's design and deployment in the workplace, and the framing and scope of the studies. The prototype serves primarily as an awareness technology and not as a behavior-change intervention; correspondingly, the studies evaluate aspects of feedback awareness, perception and interpretation in-place. That said, the broader scope of the intervention is to inspire building occupants to reflect on their relationships to climate, but it does not focus on the evaluation of their behavior in relation to AQ. Broader behavioral data – e.g. how the intervention changed participants' actions and behavior in daily life – are beyond the scope of this work and are subject for future deployment studies. The scalability of the findings concerns data-rich open plan office buildings and broadly publicly accessible building space. As the studies tool place in the same building, there are no insights around the integration of this prototypes in other contexts such as the domestic workplace; any deployments in other contexts -e.g. domestic- need re-evaluation and re-appropriation of the existing technology. Other functional limitations of the display and studies were a) the transfer of the biomimetic metaphors to specific shape- and color-changing feedback scenarios which had its own limitations; b) the fact that limited number of modules (8) were made and used in the studies, which limited the size and scale of the installation and the associated findings; and c) the changes in data streams during the deployment case study (Study 03) were often small due to hybrid working and ventilation system in place, and the proportional color change was hard to notice.

8.6. Conclusions

Empirical insights from three evaluations studies involving the deployment of a modular, customizable, soft-robotic display uniquely contribute to the limited studies in HBI research that address the experience of biomimetic feedback and soft robotics for communicating climatic (air quality) data. Focusing on evaluating a shape and color changing configurable display for climatic awareness in the workplace, this work opens the design space of soft robotics and actuating materials in architecture for physicalizing climatic data within buildings; addressing the potential of such interventions to raise awareness on AQ and broader climate in the buildings. Further contributions from these studies to the field of HCI/HBI research include key learnings around the potential of modular soft robotics to physicalize climatic data within buildings; aspects of awareness, perception and experience of biomimetic shape and color changing feedback; and the prospect of such feedback to foster climate awareness in future smart buildings and support wellbeing in that context.

SECTION D. BUILDING ON KNOWLEDGE

DISCUSSION AND CONCLUSIONS

Chapter 9. Discussion

This Chapter discusses key findings as presented in the empirical & design chapters, summarizing how they map under the three Research Questions and foregrounding them within recent literature to illustrate this work's contributions to the field of HBI and HCI research. It re-synthesizes key findings under a) Design themes and associated b)Design Implications for wellbeing in human-centered data-rich workplaces; which are also derived contributions of this work. Finally it concludes with a Manifesto for the future of HBI research, framing a design agenda around the use of climatic data in the buildings for wellbeing. It presents and discusses the elements of this envisioned agenda linking those with relevant projects to illustrate its potential application.

A summary of the Research Objectives (ROs) and Research Questions (RQs) of this PhD:

RO1: To map and unpack experiences of the building occupants in the quantified workplace (office buildings and home office); **RO2:** To create a design agenda to address in-place data use for wellbeing in that context; **RO3:** Based on this agenda, to design, build and evaluate a design intervention that enhances the data experience of the building occupants for wellbeing purposes.

RQ1: What are the experiences of the building occupants in the quantified workplace?
RQ2: How do their experiences inform data use for wellbeing in the buildings for work?
RQ3: What design interventions in workplace buildings can support data experience for wellbeing?

This chapter consists of the following sections:

Section 9.1. discusses key findings as presented in the empirical & design chapters and why they matter for HBI research. It maps these findings under the RQs (also stated in each chapter's introductory section); and summarizes this work's contributions in the light of new research developments.

Section 9.2. re-synthesizes key findings under Design Themes and recommendations for Human Centered Quantified Workplaces (9.2.1.) and specific design recommendations for supporting wellbeing in such buildings (9.2.2.)

Section 9.3. aligns findings & contributions and limitations to frame a design agenda for HBI research with a focus on the data collection and use of climatic data for wellbeing. Looking into the future of HBI research, such an agenda is relevant and timely. 9.3.1. presents topics of this envisioned agenda; 9.3.2. presents relevant projects that make use of this agenda.

9.1. Summary of approach, key findings and how they map on the Research Questions (RQs)

This PhD work program has explored the building occupants' experiences of quantification in and of the workplace **(RQ1)** in the context of supporting wellbeing in quantified buildings **(RQ2)**; framing design implications **(RQ3)** for the design of human centered workplace buildings for wellbeing. The experience of quantification (data collection and use) and wellbeing are inseparably discussed with the building occupants **(RQ1, RQ2);** enabling them associate data collection & use in the buildings **(RQ1)** as having a direct impact on their wellbeing **(RQ2)**, surfacing new perspectives on data ethics and data materializations **(RQ3).**

Following an exploratory - mixed-methods and design research - methodology, this PhD program has been generative in approach, with results opening up novel directions for the design space for human centered workplaces with a specific focus on supporting wellbeing**.** Broadly, the research questions afforded this generative approach to take place by prompting the exploration of new problem spaces for future research. By following a pragmatist methodology, this research evolved dynamically around unforeseen circumstances, treating them as variables to inform the contexts and settings for research, and the methods. For instance, COVID-19 shifted the focus from the office buildings and the shared workspace to domestic and individual workplaces. It also narrowed the discussion on wellbeing around the experience of air quality and feedback awareness, based on key findings in Chapter 5. In the aftermath of COVID-19 and in the forestep of great climate changes, these findings inform work practices beyond COVID-19 to support a design agenda whereby consideration of indoor climate (air quality) is inseparable from wellbeing.

Guided by a pragmatist sensibility, each thesis chapter responds to the research questions (albeit with a different focus as described in each chapter's introduction) to deliver design implications for future research in response to key findings. Although Chapters 4,5,6 mostly respond to **RQ1 & RQ2**, they produce design considerations which also respond to **RQ3**. To illustrate this, some of these key findings leading to design considerations include:

- Chapter 4: findings on the impact of physical scale on the perception of privacy in lived-in smart buildings **(RQ1)** and on the importance on making data experience-able and actionable in the buildings through physical interventions **(RQ3)**
- Chapter 5: on associations between wellbeing and perceived environmental aspects, surfacing the importance of air quality for wellbeing **(RQ2)**, and design considerations for environmental awareness feedback to support wellbeing **(RQ3).** Air quality awareness was found to be a key element to support wellbeing in the workplace.
- Chapter 6: on the link between wellbeing and perception of control of physical/digital boundaries in the workplace (Chapter 6) **(RQ2);** and novel dimensions of biophilic design to support wellbeing including social connectedness and physical activity **(RQ3).**

9.1.1. Responding to RQ1

This PhD contributed with an informed understanding of the lived-in experiences of the building occupants in the quantified workplace buildings. Relevant findings are presented primarily in Chapter 4 (shared workplace, smart office buildings) and Chapter 5 (remote/individual workplace, domestic workplace); with Chapter 6 discussing experiences of data collection and use in the hybrid workplace. Opposed to the majority of past work, this PhD discussed experiences in a real lived-in smart office building (not a laboratory) and extends the discussion to the domestic (remote) and the hybrid (domestic and shared) workplace, seeking to develop a holistic design agenda for the use of data in that space.

A key finding of this work is that quantified (smart) buildings should provide ways to experience data [40,322] in the building **(RQ1)**; supporting occupants' awareness of what data is collected and how it is (or can be) used in the building. As illustrated in Chapter 4, the building occupants considered data to be under-utilized; highlighting their need to be able to physically experience the data and its direct outcome (and benefit) of its use in the building **(RQ1, RQ3).** They referred to surfacing the data in ways that they can make informed decisions on how they use the building **(RQ1)** highlighting the importance of materializing data as a resource for action, as key for a bottom-up approach for designing human centered smart buildings (making people smarter)**.** These insights were later translated into design implications for large-scale physical displays such as modularity and customizability (both digital and physical) through the design research activities presented in Chapters 7 & 8 **(RQ3)**.

Chapter 4 further unpacked findings around scale and the perception of privacy; including physical scale and proportionality of data collection **(RQ1)** and temporal scale of data use – with data associated to secondary effects of human activity (e.g. material traces) seen as privacy friendly. As an outcome, these considerations point to specific physical and material considerations when talking about privacy in smart buildings. Design research for human-centered quantified workplaces would revolve around physical interfaces that allow 'dynamic, user-centered and tangible privacy' [5,392]. This will likely require the development of appropriate socio-digital-architectural design patterns which can be easily deployed and provide tangible ways for users to control pace of data collection, data accuracy and what data streams are appropriate to be collected and/or shared (and with whom) depending on where they are in the building **(RQ1, RQ3).** Part of the usefulness of a design pattern is the fact that once encountered it is easily understood on future occasions and is therefore translatable / transferable. Key to this is that people then develop a mental model of how it works and expectations on this basis for how they will or should expect a data-driven built environment to operate. Translating these insights into design implications; there were design considerations (Chapter 7) over the use of modular soft actuators as 'sensitivity' buttons- allowing users to alter the pace of data collection as well as how much the intervention responds to the data stream. This PhD highlighted the importance of developing such patterns – physical design affordances to interact with data in the buildings- and drafted some initial considerations (further illustrated in 9.2.1.); but further research needs to take place.

9.1.2. Responding to RQ2

Beyond the experience of quantification, this PhD was concerned with how participants view data collection and use for wellbeing **(RQ2);** but also, with mapping different dimensions of wellbeing in the shared and domestic workplace to establish how these might relate with physical/spatial aspects and data collection & use**.** In Chapter 5, the association between wellbeing (valence) and perceived air quality emerged as a key finding **(RQ2);** highlighting the importance of air quality awareness for the domestic workplace and the lack of research in technology that supports this [83,422] **(RQ2).** Air quality appeared as a latent aspect determining wellbeing (including emotional wellbeing) that needs to be surfaced through appropriate interventions; as many occupants were not aware of its deterioration while working from home and were solely depended on their sense of smell to make judgements (relevant quotes in Chapter 5 – domestic workplace- but also in the shared/office building in Chapters 4, 6). Although these results were heavily impacted by COVID-19, the concerns over air quality remained after the return to the workplace. Currently, the ongoing research interest for air quality and climate monitoring – see for instance wearable/ portable air quality sensors such as Luftio[181], domestic air purifiers[182] and research on IoT air quality systems [174] - illustrate both the existing research gaps and the emergence of a wellbeing-oriented research agenda in which air quality plays a key role.

Moreover, Chapter 5 findings underlined the importance of data feedback on aspects of wellbeing for the domestic workplace **(RQ2)**; framing particular design dimensions for ambient/physical feedback systems that can be deployed in shared and domestic context **(RQ3).** These include portability (being able to move around the house); integration to different personalized workplaces (technology that is embedded to the domestic feel and does not stand out); parametrization of input (being able to track parameters such as dimensions of noise, temperature or mood, and make associations between aspects of self and environment) and self- tracking / archiving (allowing overview of data history and space for self-reflection through diary entries).

Data awareness was seen as a resource for action to occupants' feeling of control over their environment, also linked to aspects of their wellbeing in the buildings **(RQ2)** (see Chapter 6). Informed by COVID-19, Chapter 6 validated past findings with regards to wellbeing concerns over air quality, and the importance of air quality awareness in both the shared and the domestic workplace **(RQ1, RQ2).** Chapter 6's major finding includes the feeling of control over one's environment as a key aspect of wellbeing prompting to consider feedback technologies that support physical and digital (data) control of feedback customization **(RQ2, RQ3).** Chapter 6 co-design activity further framed novel design dimensions for climatic feedback within biophilic and biomimetic design space; speculating on solutions that imitate instrumented plantings or support collective care for the indoor natural environment **(RQ3)**. An interesting

[181] https://dashboard.luftio.com/
[182] https://www.ikea.com/gb/en/cat/air-purifiers-49081/

finding related to olfactory feedback (the smell of plants) and the use of air flow (together with ambient movement) as a feedback strategy **(RQ3).**

9.1.3. Responding to RQ3

Responding to the key finding on the importance of surfacing air quality data for awareness (as a key element for wellbeing in the buildings), and through utilizing some of the design considerations presented in each Chapter, this PhD work speculates on the design of novel biomimetic feedback for climatic data **(RQ3)** – work presented in Chapter 7 and 8. ActuAir is a modular, pneumatic, color and shape changing intervention that communicates air quality (and broader climatic) data in the workplace (Chapter 7). In Chapter 8, I documented the experiences around this intervention to evaluate it and speculate on the design futures of soft robotics and actuating materials for climate awareness (Chapter 8) **(RQ3).** These key findings and design implications are discussed and synthesized into a holistic design agenda for use of climatic data for wellbeing in the section 9.3.

Chapter 7 combines design considerations as developed in previous Chapters to design and make ActuAir **(RQ3),** a modular, biomimetic, shape & color changing display; exploring the potentials of diverse soft robotic concepts and actuating materials for physicalizing climatic data. The key contributions of this Chapter relate to findings on how materials function (or don't function) when combined; including testing (and failing) thermochromic change and conductivity in silicone; testing shape change capacity and effect of different custom silicone-based designs ; attempting to eliminate inflation (pumping) noise; and testing material, inflation & light effects and animated sequences as ways to communicate information. Chapter 8 contributes design considerations to the application of such a soft robotic & actuating materials design agenda for climatic awareness purposes **(RQ3),** through evaluating ActuAir in-place. Key findings include: a) circular modular arrangements prompted to spatial associations, representing data from an 'area' of the building; b) light (when combined with inflation) was seen as material, inseparable from materiality (silicone); c) noise can (and should) be used to draw attention in large shape changing displays, (instead of eliminating noise, it provides opportunities); d) light is key for shape-change interpretation in-place – i.e. both using spotlights for enhancing outlines through shadows, but also through using LED's animated sequences; e) biomimetic form and materiality can create intuitive associations with climate and promote conservationist attitudes (i.e. energy concerns) and f) animated green-to-red light sequences together with inflation is successful mechanism to express accumulation of positive and negative climatic aspects (including CO_2), and was intuitively understood. The above design implications are framed to guide the design and deployment of physical, modular and soft robotic interventions (see section 8.5) that seek to engage building occupants with climatic data for awareness purposes.

Summarizing, this PhD contributes a) findings on aspects of the building occupants' experiences in quantified workplaces **(RQ1)** relevant to their wellbeing **(RQ2)** b) based on these findings, design considerations relevant with the human-centric use of climatic data in the smart buildings for wellbeing **(RQ3);** framing a novel physical design agenda for HBI research with a focus on biomimetic feedback for climate awareness.

9.2. Design Themes & Implications for human-centered quantified buildings

Key findings in Chapters 4, 5, 6 and 8 are summarized below, and then discussed in the context of *Design Themes (DTs) and associated Design Implications (DIs)* for human-centered quantified workplaces, as the core research contributions of this PhD to the HBI research field.

9.2.1. Design for human-centered quantified workplaces (RQ1).

Based on the above key findings, the design considerations presented in each chapter are synthesized into the following design themes for human-centered workplaces.

DT01. A material imperative for data in smart buildings.

A design implication for human-centered smart buildings, is that such buildings should support the embodied experience of data [40,322] through physicalizing / materializing it as a resource for action **(RQ1) (DI01).** Materializing data is about awareness (of what data is collected)- which is key for supporting building occupants' acceptability of data collection practices in the buildings – but most importantly, is about providing the opportunity to physically experience, engage with and use data as they see value. Data as resource for action was linked to the feeling of control over the built environment and was found to contribute to the wellbeing of the building occupants (Chapter 6) **(RQ2)**. This finding points to 'a return to the analog', whereby data collection and use is linked to specific physical and material representations to be meaningful. With many participants referred to their senses as the way to trust and navigate data use outcomes – e.g. in quotes on being able to smell that the air quality has improved, or to touch and feel the data outcome - the need for a more embodied approach when designing data awareness interfaces in the buildings needs to be established. By embodied, meaning interfaces that have a direct appeal to all senses [168,169] and not only vision - which is the dominant approach when designing for screen-based interactions. ActuAir provides an example of physical and material data representation that provides data as resource in multiple layers: a) a physical layer, whereby the display's modularity and plug-n-play capacity invites for physical modification; b) a material layer, whereby the data represented with light and inflation point towards experiencing air quality levels through vision, noise and touch; and c) a digital layer, whereby a control panel allows building occupants to choose specific data sources and data representation outputs (modify LED animation or speed).

Recent research advancements in neuroscience and cognitive science and the introduction of the concept of hapticity [282] in architecture (and here, in architecture as an interface) – reframe the importance of materiality and how it engages a whole-body experience. Adding to this, the aspect of physical scale [168,332] – the size of the inventions and how it relates to the body - and temporal scale [209,266,332] – slower changes, also forced by the outcomes of human activity on the buildings over time - come as design parameters; with further refences to how materiality can be used to display information in the buildings by utilizing a slower, analog and physical representation involving the whole body in the experience of it. The emerging space of programmable materials [164–166,340,402]– materials whose response to specific input combinations – human (touch), environmental (climate conditions) or digital (data)- is pre-programmed or (programmed in real time); creating interesting outputs of slow and passive yet responsive interfaces embedded in architecture's fabric in the buildings [243,246]. Metamaterials can provide physical/tangible feedback but also form structural mechanisms – see Ion's work [164,165]– that can change shape and support different use cases. Such design avenues can be further explored with a focus on data integration and sensing - e.g. real-time responses to data streams or direct user input translated into data output (e.g. see stretchable sensor by soft robotics toolkit by Harvard bio design lab[183]) - and data use – i.e. investigating design vocabularies of material variables and how they can communicate information – see Shutters [71] for instance.

Alongside the potentials of programmable metamaterials for slow feedback, research on eliminating energy expenditure of interventions or offsetting energy emissions of their production and use in the buildings is highly relevant [189,404]. Relevant to these could be materials that could 'charge' from their interactions with building occupants or support them into lowering collective CO2 emissions [17,189] Building upon early examples [189], programmability or customization of such materials is yet to be explored by future research.

DT02. A biological imperative for data materializations in smart buildings.

This PhD explored material interfaces for data awareness through particular refences to biomimicry and bioinspiration; leading to the second design implication. The second design implication is that bioinspiration for data materialization can support a more intuitive experience of data and its meaning; supporting data awareness through both imitating the body (human and non-human) and engaging with the body (provide olfactory or tactile feedback for instance) **(RQ3)(DI02).** Responding to quotes of participants which referred to being able to smell, see or feel changes in air quality (Chapter 4) [25,187,422] and to the associated design research gaps with regards to exploring embodied awareness of air quality data [20,41,71,153] – see Shutters [71] and the limited recent work on atmospheric interfaces [41]- this PhD work explored how bio-inspired material actuations (utilizing Soft robotics agenda [36,328]) can bring latent climatic aspects in the foreground of human experience **(RQ3)** through ActuAir (Chapter 7 and 8).

The key findings that drove this work into biophilia/biomimicry to support an embodied experience of data were extensively presented in Chapter 6. For instance, the participants' associations of improving wellbeing through bringing plants in the workplace (Chapter 5, 6); linking plants with air quality improvement but also with diverse other aspects of physical – e.g. physical activity - and social wellbeing – e.g. participation and connectedness (Chapter 6) **(RQ2).** These findings inspired this work into imitating aspects natural organisms including the

[183] https://softroboticstoolkit.com/smart-braids

body's function; designing a programmable and user -customizable a climatic awareness interface that imitates breathing (inflation/deflation) or CO2 accumulation in nature (representing leaves through inflation, form factors and color change. To do so, and to emphasize in materials used to represent breathing make data associations; I explored diverse material combinations (also referring to shape change and light synchronization) part of a Soft robotics/actuated materials agenda [36,328] (Chapter 7).

Derived from ActuAir's evaluation as presented inn Chapter 8, biomimicry and materiality provide unique opportunities to do support embodied awareness of climatic data, bringing metaphors from nature that also relate to human bodies as ways to communicate climatic data. Embodiment[184] [391] was supported through obtaining diverse design strategies for ActuAir's materialization; both material, functional and conceptual **(RQ3).** Biomimicry provided interesting cues towards making intuitive associations with climatic data; which is a contribution of this work **(RQ3).** Focusing on the material factors that supported the embodiment of data experience; participants touched the display or speculated that the intervention changes not only based on indoor climate but also on human movement – seeking both a personal and collective connection with the display and with the data it represents (connecting human activity to climate impact) -or expressed energy concerns with regards to the display's function.

Taking this a step further and towards rethinking embodiment in the lens of human to human and beyond human relationships; bringing human-like characteristics into physical interfaces can empower embodied experiences of climatic data- e.g. along the lines of imitating breath, imitating skin sweat etc. The questions that arise are if, biomimicry and programmable materials that imitate 'beyond human' features can support such embodied experiences; and further nurture a connection with nature and climate. Further research on the diverse aspects of biophilic/biomimetic design including participatory angles and beyond-human interactions; and how these can support climate awareness and climate-responsive behaviors in the buildings.

Finally, while this PhD contributes with the exploration of the physical and material dimension of air quality data through building and evaluating a novel intervention for climatic awareness (see ActuAir, Chapter 7 and 8) (RQ3); there are prominent research gaps related to designing olfactory, auditory and haptic interfaces for data awareness that are left for future research.

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[184] Embodied Cognition theory is a movement in cognitive science that grants the body a central role in shaping the mind. In the words of A. Wilson [391], key claims of embodied cognition are that 1) Cognition is situated: Cognitive activity takes place in the context of a real-world environment, and it inherently involves perception and action; 2) Cognition is time pressured and is understood in terms of how it functions under the pressures of real-time interaction with the environment; 3).We off-load cognitive work onto the environment. Because of limits on our information-processing abilities (e.g., limits on attention and working memory), we exploit the environment to reduce the cognitive workload. We make the environment hold or even manipulate information for us, and we harvest that information only on a need-to know basis. 4) The environment is part of the cognitive system. The information flow between mind and world is so dense and continuous that, for scientists studying the nature of cognitive activity, the mind alone is not a meaningful unit of analysis; 5) Cognition is for action. The function of the mind is to guide action, and cognitive mechanisms such as perception and memory must be understood in terms of their ultimate contribution to situation-appropriate behavior; 6) Off-line cognition is body based. Even when decoupled from the environment, the activity of the mind is grounded in mechanisms that evolved for interaction with the environment—that is, mechanisms of sensory processing and motor control.

DT03.Customizable participatory and privacy-supporting Architectural patterns

Beyond the importance of awareness as a way to support occupants' decisions in quantified buildings, the findings in Chapter 4 highlighted the need for interventions that leave space for users to control how to use the data. These findings reinforce a design agenda of smart buildings that have 'DIY' and 'open-source' dimensions [48,61] **(RQ1),** encouraging a more proactive engagement in the building's use of data [108,124], utilizing data materializations to turn responsibility and choice of actions from the building to the users [108,313,317]**.** Modularity was the design approach followed in ActuAir to support participatory customizability; ensuring that each module is independent yet connected with others though WIFI to stream data. The design principle of modularity (both in a physical but also in a digital dimensions) results as design implication to support participatory data-driven architectures **(DI03).**

Results in Chapter 4 highlighted that physical scale is an aspect that directly influences the perception of privacy and can enhance awareness and experience of data collection and use in the building [204,315] **(RQ1).** In terms of data collection, the physical scale and mass of data collection were found to be proportionate to perceived privacy (Chapter 4) **(RQ1);** whereas temporal scale of data collection – i.e. data related with secondary effects of human activity, data collected and analyzed after human activity took place– as a privacy enhancing factor.

Some of these insights with regards to physical and temporal dimensions of perceived privacy in quantified buildings were further explored when designing ActuAir as a physically and digitally customizable system. Findings relevant to scale and positionality of data physicalizations and how these relate to feedback interpretation were surfaced in Chapter 8 **(RQ3)**; showing that modules arranged in circle [204] led participants to pinpoint spatial associations to different modular arrangements – perceiving circularity as the area in a building and assigning the displayed colors to data representations from that area. Participants took that further to suggest that different areas in the building can be represented in circles; that intersecting modules can then depict the average data measurements between areas; and that modules placed in the middle of the circles represent the average of that area.

Summarizing, a Design Implication for supporting perception of privacy and user control in smart buildings, is the design of modular customizable architectural patterns for surfacing data in the workplace **(RQ3)(DI03).** These patterns could support:

- Spatialized representation of data streams in a configurable manner; i.e. similar to ActuAir, a modular installation can be configured to represent different spatial layouts and data associations.
- Physical and tangible customization to support boundaries and adapt to different spatial requirements and use cases; ability to filter what data are displayed (relevant with a specific use of space) using tangible and physical manipulations.

- Pace of data collection (temporal aspects). While it would not be advisable to allow building occupants to turn and off sensors based on the perceived harm to their privacy (as this data can be meaningful for the building's operation analysis and research purposes), it would be meaningful to allow them to adjust the 'sensitivity' of data collection sensors - to only respond to greater changes in data streams – and/or the pace of data collection – data obtained in less frequent intervals.
- Customization of data streams depending on physical & social context. Relevant to the above point; the ability to increase the pace of data collection when appropriate (for instance, in the case of CO2 when many people in a room) and decrease it when privacy is threatened or there is not a necessity (for instance, when working alone).
- Provide tangible options for users to provide consent over data being collected and establish a life-long connection to this data through appropriate archiving. Users could be able to retrieve data entries from the past (Data archiving) and understand the implications and importance of sharing this data with building managers or other users.
- Addressing energy considerations of collecting, displaying and archiving/storing data inherently in the intervention - i.e. carbon offsetting, use of passive materials for information display, reducing data collection to only the essential.

Another dimension of participatory architecture evolved around data collection ethics (Chapter 4). Bringing architects and building occupants together into the discussion of ethics and data collection practices can be meaningful for developing human-centered adaptive architectures. Adaptive architecture interiors in smart buildings should be designed and deployed through iterative phases, whereby occupants are engaged in co-designing and evaluating physical and digital aspects of building interiors. ActuAir illustrates an example template of such an integrated architecture and iterative design process framed around air quality; leaving a great breath of research yet to explored.

9.2.2. Design for supporting wellbeing in quantified buildings (RQ2).

Building on the Design Themes discussed in the previous section, here I focus on aspects of wellbeing.

DT04 Surfacing latent aspects of climatic experience (AQ) for wellbeing.

Research gaps around air quality data awareness were surfaced in the studies relevant to wellbeing in the quantified workplace **(RQ2)**- in Chapter 4, in participants quotes on the lack of appropriate use/underutilization of air quality-related data; in Chapter 5, the underlying correlation between self-reported valence and air quality; in Chapter 6, air quality discussed by participants when referring to climatic control at shared and domestic office, and various aspects of air quality present in participants scenarios. As with all environmental aspects, the subjective experience of air quality differs significantly from person to person- e.g. a few participants being very sensitive to air dryness or stuffiness (Chapters 4, 5, 6). As Chapter 5 findings suggest, and opposed to light or temperature in the workplace; air quality is often left unnoticed, which, (especially in the domestic workplace, or in meeting rooms and workplaces with lack of infrastructure) can have serious consequences to health and wellbeing [192,221,343] of the building occupants. These findings make the design of air quality awareness interfaces essential for supporting wellbeing in human centered workplaces, brought through data materializations **(DI04)**. These findings drove the design of ActuAir intervention (Chapter 7) and framed the focus of this PhD around indoor climatic data awareness interfaces as interventions to support wellbeing in the workplace **(RQ3).**

Moreover, findings suggest that there are research gaps in terms understanding how poor air quality is experienced, what other environmental aspects contribute to the experience of poor air quality – e.g. poor air circulation, smell, increased temperature or humidity – and how these different dimensions can be surfaced in ways that communicate to the building occupants intuitively. ActuAir employed biomimicry and soft robotics to address participants' intuitive connection to deteriorating indoor climate (air quality) (see Chapter 8). Findings suggesting the success of the employed strategies **(RQ3),** which included nature-imitating light/color and inflation coordination scenarios, the ability to physically customize the shape of the display, and finally, display different data sources (including temperature and humidity) to make climatic associations. ActuAir illustrates an attempt to address these research gaps **(RQ3),** which could be meaningfully explored further by HBI/HCI research communities.

DT05 Participatory biophilic environments for wellbeing

One of the recurring findings of this work was the link between data awareness and aspects of wellbeing (Chapters 4,5,6) **(RQ2).** Data accessibility and awareness was found to enhance perception of control over the environment contributing to emotional and mental wellbeing). Also, with regards to climate, awareness of air quality related data was a theme that was surfaced in domestic workplace directly linked with perceived wellbeing (Chapter 5) and a request with regards to valuable use of data in the shared workplace (Chapters 4,6). Some findings on what types of feedback might be meaningful to design awareness interfaces were surfaced in Chapter 5 (e.g. reflective feedback, wearable, non-real time); but most of the relevant design exploration in Chapter 6 gave rise to emerging biophilic concepts (later transferred into a soft robotic & actuated materials for climatic feedback) through materializing an intervention.

Biophilic design emerged as the central theme for materializing climatic data; moreover, the key finding was the participatory and physical dimensions that biophilic design entails. New dimensions that connect the experience of nature and wellbeing in the buildings highlight the potential of collective participation in constructing biophilic environments and nurturing different human-to-human and human-to-environment relationships. These participatory perspectives on biophilia connect wellbeing (and related literature) with the theme of bottom up/ participatory smart environments – where smartness comes from the building occupants, not the building itself.

Participatory architecture is about giving people agency and that they are responsible for their environments. Framed within climate and wellbeing, such participatory architectures can provide building occupants with accountability and reframe the way they relate with each other, with the buildings and the natural world. Building upon Design Themes DT02 and DT03; participatory biophilia includes creating customizable, modular and open-source architectures that utilize bio inspired materials and biomaterials **(DI05)**. My work on ActuAir (Chapters 7, 8) and soft robotics sets an example of developing such templates, which can be further explored by future work.

9.3. Rethinking Human Building Interaction research to address wellbeing in a changing climate

Based on the above Design Implications, the following design agenda was composed around wellbeing and indoor climate, and interactive materials; addressing the importance of climate awareness in the built environment to drive human behaviour drive human behaviour towards more environmentally conscious decisions and actions.

9.3.1. An HBI research agenda for the human-centered use of climatic data in the quantified buildings for work

Climate change poses unique challenges for the design of human-centred smart buildings [15,42] and Human Building Interaction (HBI) research [2,20,26,39,40]. Harvesting the potentials of vast amounts of environmental and personal data accumulated in contemporary smart buildings [40], and advances in programmable/actuating materials [6,9,11,13,22,24] and biomaterials [35,51]- see CO2 harvesting materials for instance [4]; new design opportunities for novel data interactions that address climate, health & wellbeing and behaviour in workplace buildings are emerging. These opportunities remain vastly unexplored by the HCI & HBI research community.

The HCI research community has recently been rethinking the design of climate awareness technology amidst pressing climate considerations; considering the physical, tangible, temporal and material dimensions of data-feedback in the buildings. This has included a recent breadth of research around air quality awareness in buildings [7,29,53] and different forms of environmental data feedback – see for instance Atmospheric Interfaces [12,27]; Hilo, a wearable notification system for indoor and outdoor air quality in office spaces [139,140]; or Shutters, an actuating room divider for air quality awareness [12]. Some of these projects engage with physical [7,12], tangible [5,14,43] and olfactory feedback [23] to support climate awareness, wellbeing [45,54], environmental management [16,48] and behaviour change [15,44] to support wellbeing. Yet there is plenty left unexplored in terms of designing physical, slow interactions to support climate-sensitive behaviours in the buildings.

Research on biophilia and biomimicry [28,31,36,37,54] seeks to restore the link between humans and nature as a key element to support wellbeing and human flourishing in the buildings [32]. In Adaptive Architecture, biophilia and biomimicry are employed with view to advancing building technology to support wellbeing within a changing climate - see for instance research by HBBE. Relevant research involves advancements in composite materials [1,46,49,52] – see hygroscopic materials [38], and thermobimetals [46] for responsive building

skins - bio-materials [4,18,35,38,51], and other forms of bio-engineered architecture – see algae-based architectural materials [21,35] - and programmable materials [13,24,25] and soft robotic systems [8,31,37,54] for sustainability and energy management - see pneumatic skins [17,47] use of SMA on façade elements [10,30] or interiors [33,34].
To guide future research in these topics, I have synthesized the following design research topics that address human relationships with data, materiality and physical space into a unified design agenda for HBI research that addresses wellbeing and indoor climate. Amidst these research advances in materials, there has not been a considerable effort to connect the emerging practices of architects on the one hand and interaction designers/HCI researchers on the other. Framed as Human-Building-Interaction research for wellbeing and indoor climate, this design agenda seeks to do so, producing a unified research agenda that brings research advances of adaptive and climate responsive architecture, emerging physical interfaces including programmable/actuating materials and biomaterials into the discussion of designing feedback systems for supporting wellbeing and address indoor climate in the buildings. This design agenda aims to contribute to guiding future research in Adaptive architecture and Human Building interaction, but also Interaction Design and Human Computer Interaction more broadly, into building technology for more-than-human, symbiotic relationships with the built environment in the context of indoor climate and wellbeing.

This agenda shares much with aspects of the design futures proposed by slow design [19], reflective design [41], calm technology [50] and physical/tangible computing [3,27]; here with a specific focus on human – data - climate relationships in buildings. This includes technologies that foster a re-establishment of human relationships with climate through physical and material data representations in buildings; design research that links wellbeing with the experience of climate; research on ethics of data collection and use in buildings for climate management - including ethical considerations over behaviour-change and climate; and broader research in areas of programmable materials, soft robotics, shape changing interfaces, physical displays, adaptive architecture, biomimicry/biophilia and participatory architecture under climate change.

The following diagram shows key dimensions of the agenda, and aspects that comprise them:

- Data Ethics; including tangible consent, negotiating privacy (pace/scale/mass), data display & sharing ethics - Design Themes DT01, DT03 (findings as per Chapters 4,6)
- Climate (Indoor) & Wellbeing associations – Design Themes DT04, DT05 (findings as per Chapter 5,6);
- Architecture as an Interface – Design Themes DT01, DT02, DT03 (findings as per Chapter 7,8) .

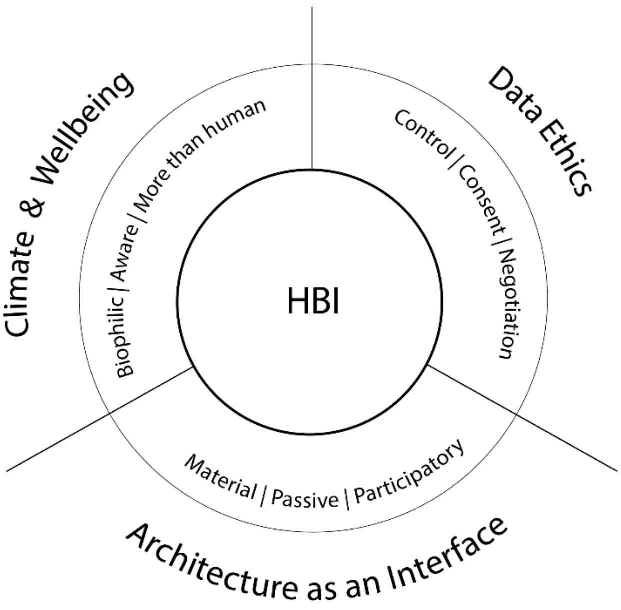

Figure 120: Dimensions of a design agenda for HBI research futures addressing indoor climate and wellbeing. The dimensions and aspects illustrated are a visualization of the Design Themes and Implications discussed in the above section (9.2.).

In terms of guiding future design research, three research themes and associated research topics have been identified: People & Behaviour in buildings; Climate Data & Context; Design & Technology and Interfaces. Topics include but are not limited to:

People & Behavior and Agency in smart buildings (under climate change)

- Climate-sensitive Behavior awareness & behavior change in place.
- Collaborative & symbiotic interactions in buildings
- Human-to-human and more-than-human interactions
- Climate awareness and health & well-being
- Towards net-zero: framing human-building interactions under net-zero and carbon-offset strategies.

Climate Data & (Spatiotemporal) Context

- Mapping aspects of climate & climate change in buildings – e.g. complexity of indoor air quality
- Methods for mapping experiences relevant with climate change and data in the buildings: quantitative, qualitative, and mixed-methods approaches; process-oriented methods; research through design.
- Data collection & data harvesting – new approaches to sensing
- Human-AI interaction and climate prediction
- Ethics of climate data; sensing and privacy.

Design, technology and Interfaces

- Biomimetic & biophilic interfaces
- Self-powered / passive & zero energy interfaces
- Nover feedback strategies – e.g. haptic, embodied etc.

- Actuating / Programmable materials
- Biomaterials & feedback

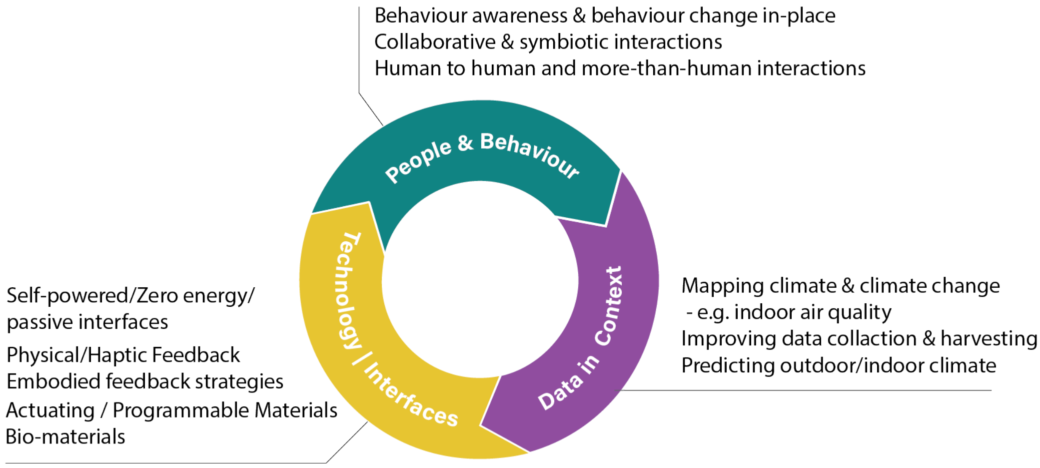

Figure 121: Topics of interest of this agenda.

9.3.2. Example projects from the application of this design agenda.

The following projects are discussed in the context of the above design agenda; illustrating potential applications and research avenues.

9.3.2.1.Robotically augmented biomimetics.

Combining robotics with the utilization and control of novel materials can have great impact for large scale interventions; such as adaptive façade elements. An example, The Augmented Thermochromic Façade (see Figure 115) [189] uses robotic control to paint on the thermochromic fabric by means of a heated brush that regulates the color change configuration. The traditional sensor-driven robotic mechanism augments the natural response of the material to induce specific non-mechanical change at any location in the area.

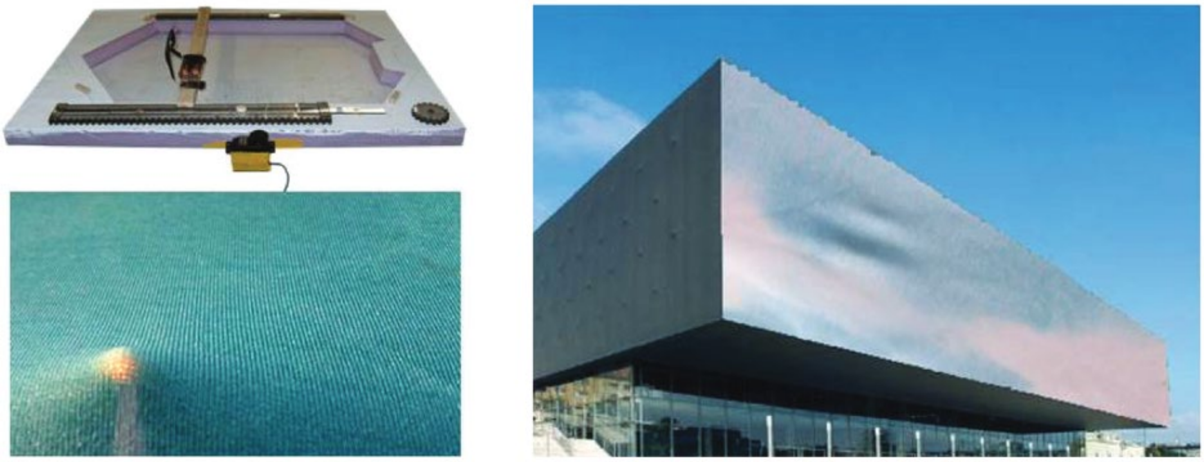

Figure 122: The augmented thermochromic façade **[189]**.

The Sisyphus Façade system (Augmented Electro-Magnetic Façade) [189] relies on the specific control of an electromagnetic array of metallic spheres on an acrylic skin (Figure 116).The magnetism controls the concentration of these spheres on the surface, giving a sense of distributed robotic control. The effect is naturally random, creating a slightly different pattern every time with the same controlled effect.

Figure 123: Sisyphus Façade System

Combining soft robotics /actuating materials with rigid robotics can expand the potentials for developing passive-energy building elements at large scale, while also providing climatic feedback. Future research can explore similar biomimetic low-energy processes translated into material actuations; programming of such structures in ways that provide accessible feedback while reducing energy consumption.

9.3.2.2.From soft- to bio-robotics: Programmable 'alive' materials

Bio-materials can be introduced in combination with robotic elements to regulate their response; also benefiting from the potential of such biomaterials to reduce (or even to produce) energy to power robotic structures. As an example, the Augmented Slime Mold Bio-Façade (Figure 117) [189] uses biomaterials to minimize energy use and mechanical complexity. Slime mold possesses a natural ability to provide varying levels of transparency as it passes through multiple phases of growth. The growth cycle, and consequently the esthetic effects and patterns, are controlled through the robotic manipulation of depositing and retrieving a regulated texture of growth medium, and food quantity, to specific locations.

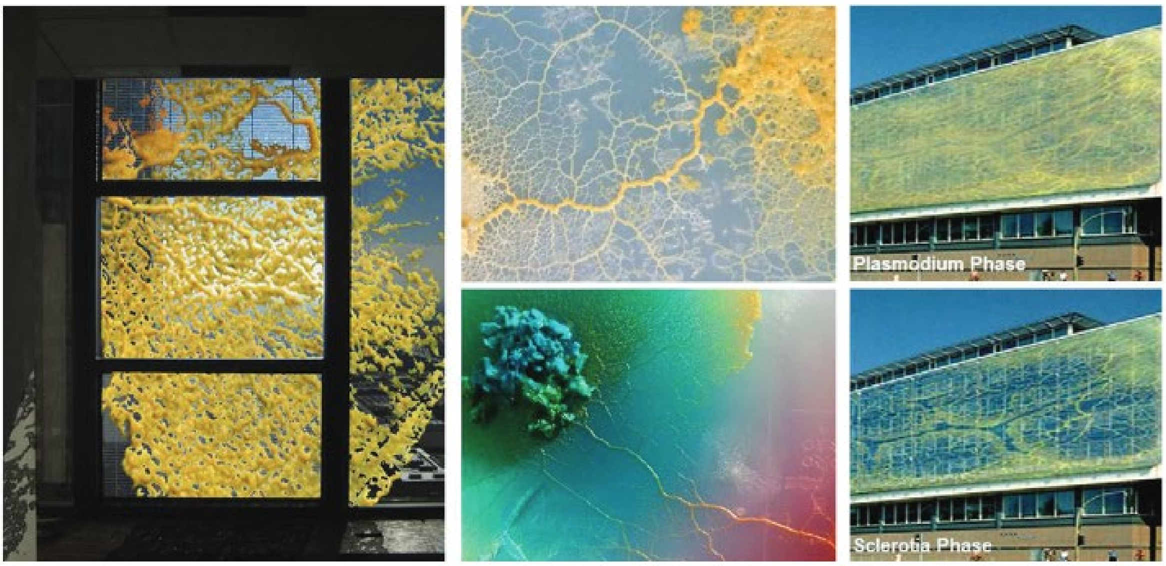

Figure 124: Bio-Facade

Again, there are HCI research challenges with regards to transferring biomaterials into interiors, integrating them into aesthetically pleasing and accessible awareness interfaces. Material-based actuation could potentially lead to "zero-energy" buildings. An example of these efforts is "Solar Leaf" photo-bio-reactive façade prototype. It features a layer of microalgae between two sheets of glass that generates biomass and heat as renewable energy resources. Recent projects such as “Demonstrating a Fabricatable Bioreactor Toolkit for Small-Scale Biochemical Automation is a project that provides a toolkit (software and hardware)” demonstrate attempts of creating accessible open-source tools to program bio-reactors and bio-materials as the above. This is of particular interest to HCI researchers; alongside with designing and programming accessible feedback strategies for biomaterials.

9.3.2.3. Participatory Architecture and net-zero

The projects below explore the potentials of participatory engagement in nurturing responsible relationships with climate.

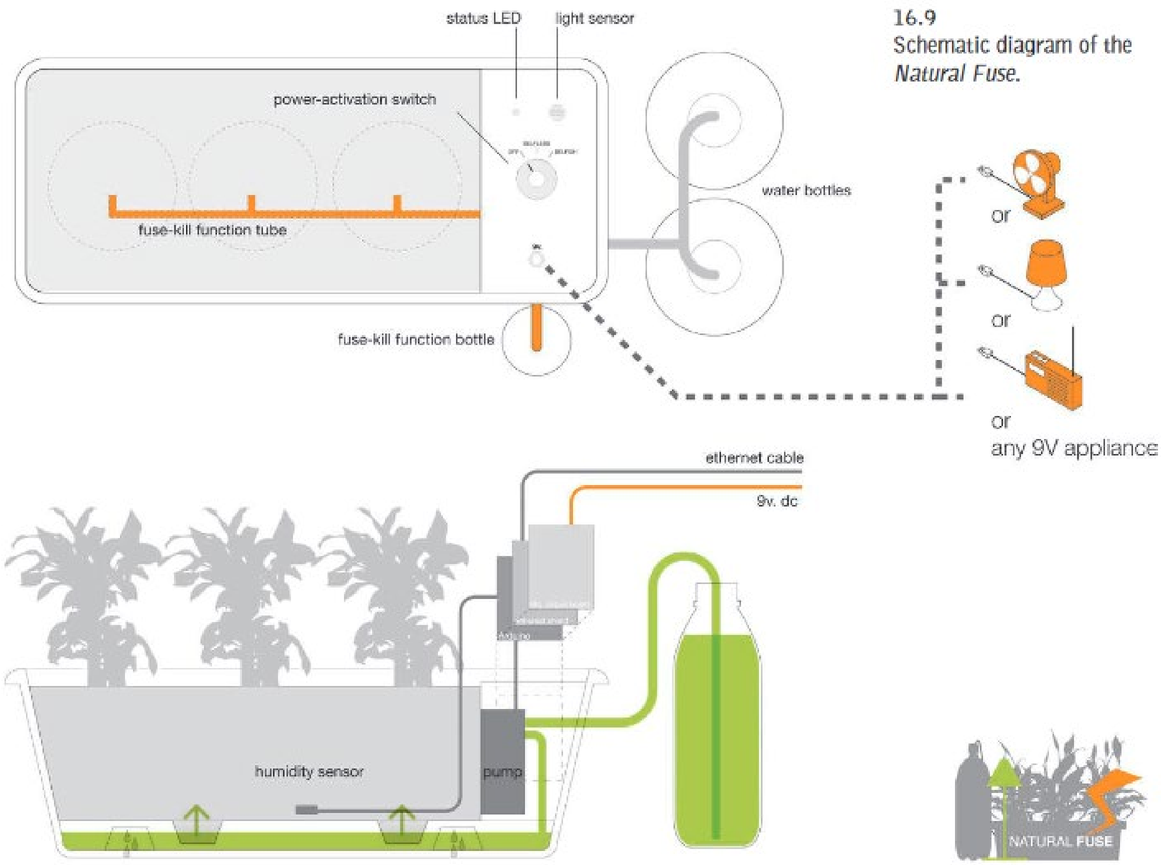

Figure 125: Natural Fuse

Natural Fuse (now distributed in households in London, New York, and San Sebastian) [189] is a project about carbon dioxide offsetting through natural, distributed carbon capturing. It is a micro-scale carbon dioxide overload protection framework that works locally and globally, harnessing the carbon-sinking capabilities of plants. The carbon footprint of the power used to run these devices can be offset by the natural carbon-capturing processes that occur as plants absorb carbon dioxide and grow [189]. Natural Fuse units take advantage of the natural carbon capturing capacity of plants to produce electricity. Natural Fuses allow only a limited amount of energy to be expended; that amount is limited by the amount of CO2, that can be absorbed by the plants that are growing in the system: the natural "circuit breakers." Each Natural Fuse unit consists of a houseplant and a power socket (Figure 118). The amount of power available to the socket is limited by the capacity of the plant to offset the carbon footprint of the energy expended: if the appliance you plug in draws too much. By networking them together, the plants are able to share their capacity and take advantage of carbon- sinking surplus in the system since not all Natural Fuses will be in use at any one time. If people cooperate on energy expenditure, then the plants thrive (and everyone may use more energy); but if they don't, then the network starts to kill the plants, thus decreasing the network's electricity capacity. The above project shows the potential of participatory architectures to nurture responsible relationships with climate and invites future research in this direction.

Chapter 10. Conclusions

This PhD Thesis responds to the timely topic of the quantification of the workplace and the emerging wellbeing challenges of inhabiting sensory-rich workplaces prior, during and post COVID-19. This PhD Thesis adresses relevant research gaps within Human Computer Interaction (HCI) and Human -Building-Interaction (HBI) research through a design-led and mixed-methods methodological approach; responding to the topic in a three-fold way. First, it unpacks the experiences of the occupants of a quantified building while working in the office, at home and in hybrid; discussing their experiences of data collection and use in these contexts. Second, it maps the emerging wellbeing challenges in the shared, domestic and hybrid workplace; and discusses how these might inform data use for supporting wellbeing in the buildings for work. Third, it addresses the research challenges through designing, deploying, and evaluating a data awareness interface as a means to support wellbeing in the workplace; investigating the experience of air quality data and its representation through a physical customizable display. Key contributions of this PhD Thesis to the field of HBI research include empirical knowledge on the human experience of data collection in the shared and domestic workplace and its use in the buildings for wellbeing purposes; design recommendations for the human-centered design of data-rich workplaces; and design implications for architecture-as-display for environmental feedback in the context of workplace wellbeing. Ultimately, it is my hope with this thesis, that I might open new avenues for research in HBI that will galvanize new and renewed efforts towards exploring how digital technology might be brought to bear upon the design and operation of human-centered buildings. Specifically, in ways which will stand to have a significant benefit towards our achievement of a sustainable future while supporting the wellbeing of the building occupants. A future that will be safer, healthier and more sustainable for all.

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