Interactive Breezemaker

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A Design Framework for
Personal Environmental Control Systems Utilizing Elevated Airspeed

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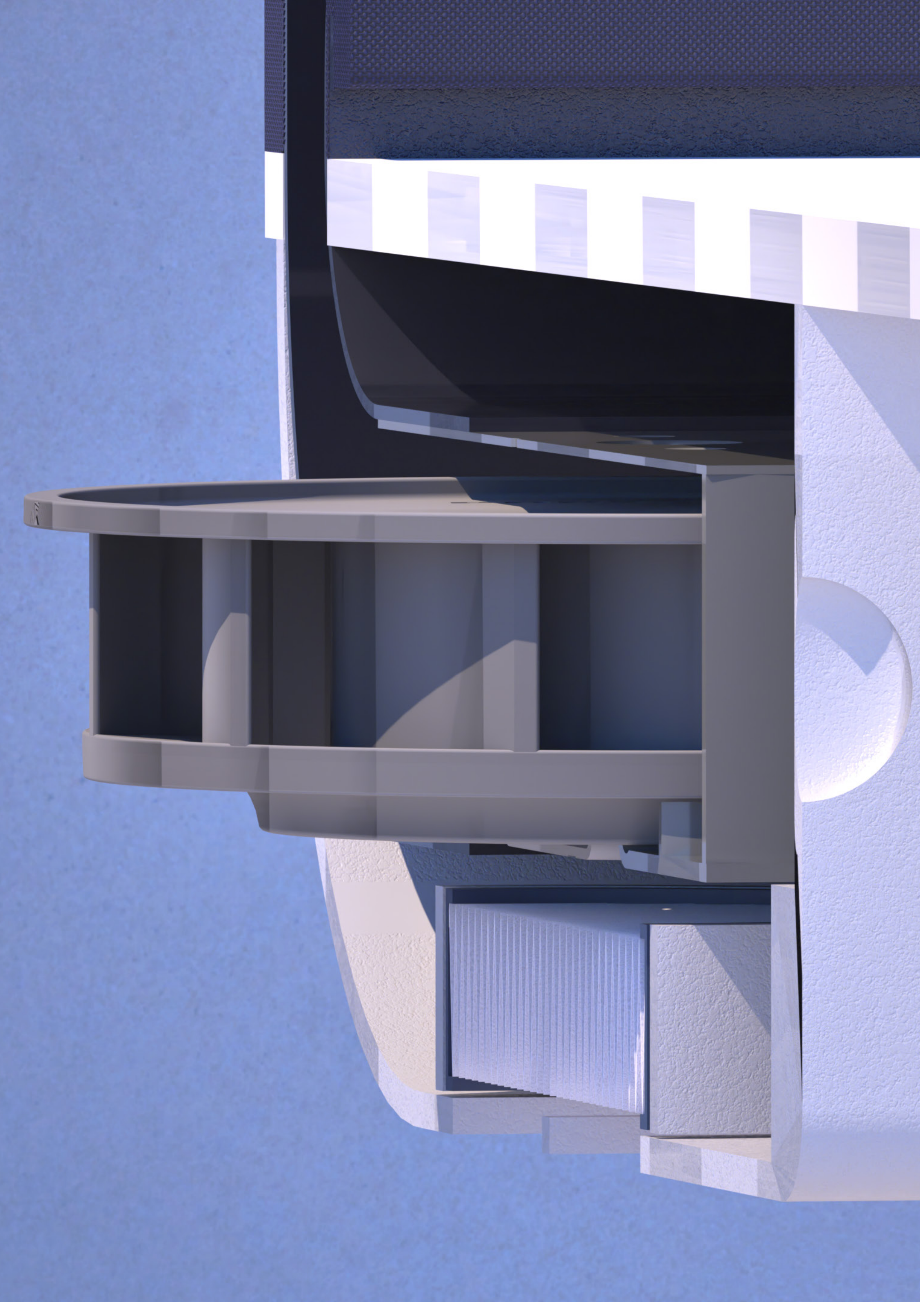

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After months of working on this master's thesis, I can say that this might have been the most valuable and educational part of my studies at the Faculty of Architecture. Growing up in a contractor's family, where I always had to pass through the workshop where 'de jongens' were always busy, I found my fascination for the built environment. When I moved on to university, I realized that not only the construction process was important, which I already had a good grasp on, but also how to come up with a good design. This is something I have learned over the years at this faculty, culminating during this thesis in the creation of an evidence-based framework and design.

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Abstract

This study investigates the provision of personalized air velocity for occupants in open-plan offices during summer, aiming to enhance comfort and productivity while conserving energy. By addressing dissatisfaction arising from limited control over environmental conditions, this research proposes a solution integrating individualized airspeed and distribution control within open-plan offices in temperate maritime climates.

Building upon the significant energy consumption associated with Heating, Ventilation, and Air Conditioning (HVAC) systems, this research underscores the potential for energy savings by locally increasing the airspeed instead of cooling the air. Furthermore, it emphasizes the importance of individual control in enhancing workplace satisfaction and productivity. Employing a theoretical framework of perceived control, the study delineates environmental and perception domains crucial for effective implementation.

Through interviews and theoretical analysis, a design framework is developed, focusing on control, performance, and robustness. The study identifies essential design factors and criteria, distinguishing between must-have and optional elements. Notably, user preferences and environmental constraints shape the design process, highlighting the need for tailored solutions.

Key findings underscore the significance of user-centric design, considering factors like noise, draft avoidance, ergonomic placement of controls, and device flexibility, ensuring compatibility with the office layout's adaptability.

This research contributes to the advancement of personalized environmental control systems, offering insights applicable to various workplace settings and climatic conditions.

Keywords: *environmental control, elevated airspeed, perceived control, user-centered design, personlized air velocity, open-plan offices, thermal comfort*

Summary

This research explores how personalized air velocity can be effectively provided for occupants in open-plan offices during summer. The objective is to design an effective method that creates increased airspeeds and air distribution, which can be individually controlled within open-plan offices in temperate maritime climates. This solution should be integrated as a building product, contributing to a comfortable and productive thermal environment in an energy-efficient manner.

Currently, 40% of the total primary energy consumption in the United States and the European Union is attributed to buildings, with 20% allocated to Heating, Ventilation, and Air Conditioning (HVAC) systems systems (Cao et al., 2016). By reducing air cooling and compensating with increased airspeed, energy savings between 10% and 28% can be achieved (Schiavon & Melikov, 2008). According to Leesman (2023), temperature is the second most significant factor of office dissatisfaction, with only 31% of individuals satisfied and 69% dissatisfied. This dissatisfaction stems from the lack of control over their environment at work, unlike at home. As thermal comfort varies greatly among individuals, especially in diverse work environments, it is crucial to provide options that can be adjusted by individuals. Furthermore, giving employees more personal control over their environment has been shown to increase productivity (Leaman and Bordass, 2000). This is particularly appealing to businesses, as energy costs represent only 4% of total company costs compared to 85% for employee salaries (Pellegrini-Masini & Leishman, 2011).

Literature Review

The theoretical framework used is the theoretical framework of perceived control. Perceived control consists of three domains: environmental, perception, and behaviour. Different factors play an important role in these domains. The domains of environmental and personal together form the constraints that ultimately determine the resulting behavior.

In the environmental domain, it is important to understand the social context, such as work activities and dress code. Where the work activity level in an open-plan office ranges between 1 and 1.4 met for seated and standing desk work, and the clothing value lies between 0.4 and 0.6 clo during summer. In the physical environment, it is important to know what temperatures and humidity levels fall within the scope, based on climate and standards. This research focuses within the limits of 40-60% humidity and between 24-28 degrees inside buildings. From this, it emerges that the air velocity to be highly accurately adjusted is between 0 and 1.5 m/s.

The perception domain involves the four elements of stimuli, experiences, expectations, and evaluations. Stimuli are defined by quality, intensity, and duration. Experiences are defined by a strong internal or external locus of control and existing knowledge of control strategies. Linked to expectations is perceived control, which is defined by actual control, fine-tuning capability and speed of response. These forms of control are linked to the final preferences one has, with the preferred air velocity between 0 and 1.5 m/s. These two domains together are both linked to the constraints associated with what control is actually available.

The two domains, namely perception and environmental factors, are further subdivided into the categories of control, performance, and robustness. Within these categories, specific factors emerge that are crucial for the effective implementation of a breezemaker device in an open office environment.

Interviews

To find out users' experiences and expectations, in addition to experts' insights and expertise, interviews were conducted. The interview method was semi-structured, allowing for more in-depth exploration and probing (Van Boeijen & Daalhuizen, 2010). The interview was divided into the areas of performance, control, and robustness, where respondents could both give verbal answers and draw pictures. In addition, questions were explored in depth using the 5W1H method.

Important results show that people perceive applications in a built environment that generate increased airspeeds as annoying, unlike in a car. In addition, people are often not aware of the many factors that influence their thermal comfort, usually only think about temperature. A key insight is the method of communication, people er not interested in higher or lower air speeds but in the effect: colder or warmer.

When designing, consideration must be given to two types of users. For people with an internal locus of control, a fine-tune button is sufficient. For people with a strong external locus of control, an automatic preset function is better because they do not have the confidence to achieve the desired airspeed themselves and rely more on an average setting than on their own feeling. Noise or drafts felt by others are unacceptable in a personal environmental control system.

Another important result is understanding the division of roles and the timing of people's involvement in building and office design. The role of the interior architect should not be underestimated. If there are not enough adaptable options, they will not implement the design from the beginning. Users will later make adjustments themselves, which can lead to frustration for facility managers as they lose control over energy consumption, undermining the goal of energy conservation.

Design Framework

After bringing together the theoretical framework and the interviews, a design framework emerged that focuses on three areas of control, performance, and robustness, but now with validated factors forming the design drivers. In the design drivers, a distinction was made between factors that must be implemented and those that could be implemented. After this, the factors that were in the must group were split into design criteria or design requirements, with the criteria being able to control the requirements.

Certain factors serve a higher purpose, while others simply need to be implemented. For example, an on-off button and an automatic button are primarily functional additions. However, the responsiveness of these buttons and the system serves a higher purpose. Therefore, when implementing functions, it is important to determine what the criteria are and what the requirements are.

When identifying factors, it is important to look at how these factors relate to each other and to understand the hierarchy. The scale level is crucial here. The research identified many factors that are essential for a well-functioning system. However, implementing too many factors can lead to a less effective design due to the different levels of importance among factors.

In conclusion van het framework, it is important that a device can generate an airspeed of 0 to 1.5 m/s, aimed at the head and arms, with precise fine control. The system should have both an on-off button and an automatic button, with the fine control of both the precise adjustment per body part and the intensity being crucial to receive the desired airspeed. The controls should be located in the second and third ergonomic zones, while the device itself should be placed in the third or later ergonomic zone. The primary features of the interface should function properly before adding additional features such as a digital interface and memory functions can be added. All of this should be done in a way that provides feedback visually and tangibly without producing disruptive noises for other users in the space. The airflow should precisely reach the desired body parts without causing drafts for other users in the space. Additionally, the device should be visually integrated and maintain the flexibility of the layout.

Demonstration of the Framework

Based on this framework, a design was made. By means of the morphological chart method, which divides the design into sub-functions, many different designs were made focusing on specific sub-functions. Some sub-functions are suitable for assessment using the Harris Profile, where the design criteria stated in the framework serve as criteria for the Harris Profile.

From this assessment, three main forms emerged: a solution placed on the work surface, a solution acting as a partition between desks, and a ceiling-mounted solution. After developing these main forms and implementing the sub-functions, this led to three design concepts. Through validation with other designers, the decision was made to further develop the partition solution into a final design. This design primarily consists of two elements: an acoustic panel mounted on the desk functioning as a pressure box, allowing air to be directed towards the occupant through openings that rotate 360 degrees. This is controlled by a user-centric interface featuring a fine-tune button referencing the operative temperature and a memory capability function with preferred settings. At the bottom of the desk, a container houses a fan combined with a HEPA filter, reducing maintenance needs. These two airtight connection elements join the two main components together.
The two elements are connected by an airtight component that directs the air from the fan into the panel.

Recommended further Research

This study lays the groundwork for further exploration into personalized environmental control systems. While this research focuses on a summer scenario and the use of increased air velocity, numerous other factors, such as winter situations, acoustics, lighting, and air quality, may come into play, especially in the workplace. The methodology employed in this study can serve as a guideline for outcomes in other areas. Furthermore, research can be conducted at the architectural level to explore the possibility of integrating these systems into central systems without sacrificing flexibility. Additionally, the interface can be further investigated with input from experts in industrial design to develop and validate the conditions outlined in this study. Moreover, an intriguing question in the realm of mechanical engineering may be how to achieve air velocity more effectively without generating noise.

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01

INTRODUCTION

1. Introduction

1.1 Background

Offices constitute a significant portion of our building stock. Over the years, offices have taken on various forms, from small meeting rooms, open-plan spaces, burolandschaft to action offices (Saval, 2014). What they all have in common is the fact that a diverse group of people spends several hours a day in the same space.

In temperate Maritime climate, these structures are primarily made to hold on to heat inside. Buildings are getting airtight and more insulated (Ürge-Vorsatz et al., 2015). The number of devices per person has significantly increased, increasing the internal heat load of buildings (Kim et al., 2018). In addition, temperatures are rising due to weather changes, particularly in the summer (Fürtön et al., 2022). Furthermore, a lot of offices have big glass facades that add a lot of heat load and sometimes make air conditioning necessary even in the off-season (Yu et al., 2015). Therefore, it is essential that we focus more on these buildings' cooling systems (Elnagar et al., 2023).

Currently, if there is active cooling in the building, it is often entirely based on lowering the air temperature (Santamouris, 2016). Cooling the entire air temperature consumes a significant amount of energy, and is this the most sustainable way to ensure comfortable thermal conditions? Nowadays, 40% of the total primary energy consumption in both the United States and the European Union is attributed to buildings. Out of this, 20% is already allocated to the use of HVAC systems (X. Cao et al., 2016).

Within the Fanger model (1970), there are additional factors that can contribute to achieving a pleasant indoor climate. One of these factors is increasing air velocity (ASHRAE ,2017). By reducing the cooling of the air and compensating with an increased airspeed, this approach can lead to energy savings ranging from 10% to 28% (Schiavon & Melikov, 2008).

Therefore, temperature is the second worst factor contributing to office dissatisfaction, with only 31% of individuals satisfied (Leesman, 2023). Currently, climate control is often centrally managed in office buildings (Day & Gunderson, 2015). Whether it's a central thermostat or a centralized climate system determining the temperature, users have little to no influence on their thermal comfort. Even when there is an option to control the climate, users often struggle to understand the abstract controls (Karjalainen and Koistinen, 2007). Moreover, there is a lack of knowledge about essential factors that need to be implemented to achieve an effective personal environmental control system. This combination leads to conflicts in preferences, for example, disagreements on whether the temperature should be higher or lower, or if the window should be open or closed (Marín-Restrepo et al., 2020).

Numerous studies, including Dear et al. (1997), have shown that it is crucial for individuals to have the ability to exert influence in these situations. Furthermore, companies observe that by giving their personnel more personal control, their productivity increases (Leaman and Bordass, 2000), which is naturally very attractive for businesses, as energy costs account for only 4% of the total costs of a company compared to the salaries of their employees, which constitute 85% of the total costs (Pellegrini-Masini & Leishman, 2011).

The fundamental reason why humanity constructs buildings is described in 'An Essay on Architecture' (The Primitive Hut) by Marc-Antoine Laugier (1753).

> ''The main purpose is to provide shelter in order to be safe and feel comfortable against wild animals and the weather (Laugier, 1755). ''

Nowadays, buildings have become much more complex and must meet numerous requirements. However, it seems we have forgotten the primary function of a building: to provide a comfortable and functional space for its users. In the previous century, the idea emerged that the advent of mechanical ventilation could solve everything, and users would be best served by a centralized system. In addition, we often see a lack of a holistic approach in the built environment. As a result, our buildings consume a tremendous amount of energy, and users have little to no control over their own thermal comfort.

1.2 Problem statement

Due to increasingly well-insulated office buildings, there is a potential risk of overheating and high cooling demand in summer situations. Currently, buildings either lack cooling systems, or the emphasis on temperature control primarily involves reducing air temperature, which is highly energy-intensive. Additionally, many users have little to no control over their thermal comfort in large open spaces such as open-plan offices, which means they feel less comfortable and are also less productive.

Increased airflow can be produced by a variety of applications, such as movable windows, integrated desk fans, ceiling fans, and desk fans. These programmes don't satisfy users' needs since they can't do what they're supposed to do without interfering with other functions, which is inconveniencing. Furthermore, a lot of applications don't have a well-integrated design within the current built environment, which lowers the quality of the user experience and diminishes the willingness of, for example, interior architects and owners to invest in them. It is about the lack of a holistic perspective and method that connects technology and design. Het is daarbij zaak niet alleen om een in te gaan op In addition, other methods of airflow can be investigated in contrast to what is already available on the market.

A possible solution to these problems is to locally increase airspeed with an device that can be controlled both locally and collectively to guarantee comfortable thermal comfort, instead of lowering the air temperature for cooling. The goal in resolving this issue is to produce an open-plan workplace solution that is more user-centric, energy-efficient, and smoothly integrated in both existing and new offices. The thesis focuses on the application of an alternative building product that offers better air distribution.

The problem is formulated as follows:

> *''Develop an evidence-based framework for personilzed air velocity for occupants in open-plan offices in a temperate maritime climate, aimed at enhancing comfort and productivity, and illustrate this through a design solution''*

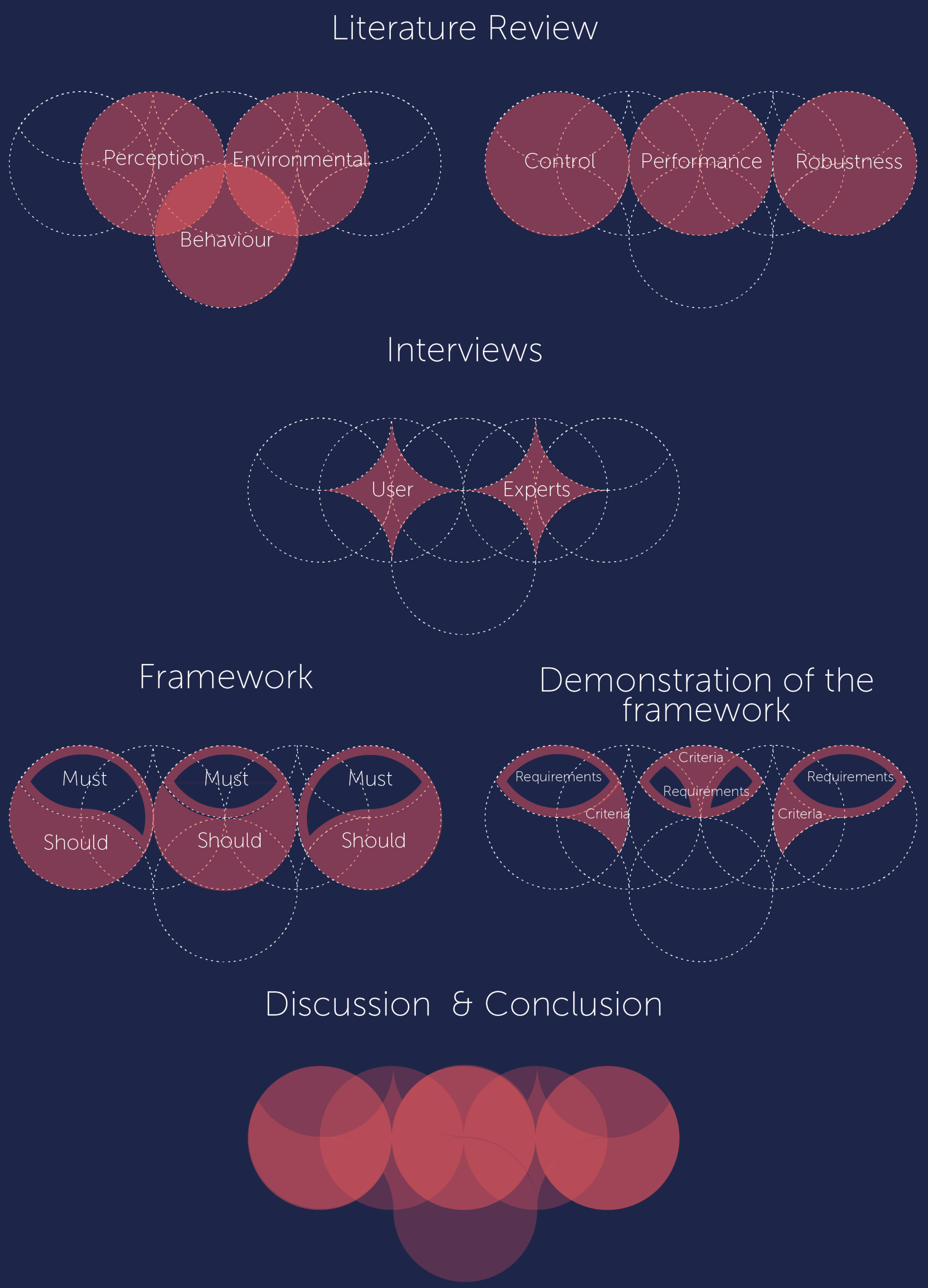
1.3 Research questions

To address the problem statement above, the following main question has been formulated:

- *How can we develop an evidence-based framework to implement personalized air velocity for occupants in open-plan offices during summer and design an effective solution?*

To answer the main question, the following sub-questions have been formulated:

- *What is the effect of increased airflow on an individual's thermal comfort, considering parameters such as metabolic rate, clothing level, radiant temperature, air temperature, and humidity levels?*
- *What is the effect of personal control on applications providing elevated airspeed?*
- *What are the advantages and disadvantages of various applications that enhance airflow to promote thermal comfort?*
- *How do we provide an effective methodology for designing a breezemaker application in open-plan offices?*
- *How can we effectively integrate a breezemaker application integrated in open-plan offices?*



1.4 Methodology

This thesis is methodically divided into 5 phases:

1. Literature review
2. Interviews
3. Framework
4. Demonstration of the Framework
5. Disscussion & Conclusion

The first phase mainly consists of a literature review where various sources are juxtaposed. This information is sourced from Scopus, Google Scholar, and the TU Delft Library. In the first chapter, the heat balance of the human body is explained, detailing the effectively coolable parts of the human body through convection. Subsequently, the fundamental thermal comfort factors are discussed in conjunction with the desired air velocity. Then, a few characteristics of drafts are discussed.

The second part of the literature review discusses perceived control, where a conceptual model is referenced. This conceptual model forms the basis upon which the rest is built. Factors in the realm of control, performance, and robustness are added through existing literature. As a conclusive part of the literature review, an analysis is conducted of existing airflow applications using the Weighted Objectives Method in combination with the Harris profile.

The second part comprises interviews. Due to a knowledge gap regarding the experiences and expectations of both users and experts, this is investigated through semi-structured interviews. In this section, the criteria are validated, specified, or even newly added. This results in a hierarchy of design criteria.

The third part consists of establishing a framework. This serves as the bridging section between the literature and interviews. The criteria are known in conjunction with a hierarchy, from which a framework is devised consisting of three elements: Design Drivers, a list of requirements in a more textual form to better convey the design direction, a workflow containing design considerations and design criteria, and an ergonomic manual.

The final part primarily demonstrates how to utilize the framework. The various design considerations essentially function as subfunctions of the product, each of which can be designed separately. These are developed using the morphological chart method. Three of the design considerations are evaluated against the design criteria using a Harris profile. These considerations pertain to cooling the arms, head, or feet. Subsequently, a general interface applicable to all design concepts is presented, followed by the presentation of three different final design concepts.

1.5 Research objective

The aim of the research during this thesis is to determine under which conditions a personal environmental control system should operate, which design criteria are known from the literature to achieve an effective design, and which applications are currently on the market. From this comparison, it was found that the existing applications are not sufficient.

Furthermore, there is a knowledge gap in the specific area of experiences and expectations of users of office spaces regarding devices that utilize increased airspeed. Additionally, it is unclear what the relationships are between various experts in the field, all of whom contribute to such devices.

The subobjectives addressed in this study are as follows:

- *Overview of current parameters for open-plan offices in office buildings during summer in maritime temperate climates, focusing on increased airspeeds.*

- *Comparison of existing applications that provide increased airspeed in the current field.*

- *Determine the experiences and expectations of both users and experts regarding a device that generates increased air velocity.*

- *Delivering a report and presentation with fundamental knowledge and concepts that recommend further research directions.*

1.6 Design objective

There is also a design challenge concerning personal environmental control systems based on elevated airspeed. Important factors emerged from the research, specified and validated through interviews. As a design objective, the aim is to develop a design framework that can be utilized by other designers. Furthermore, the framework is demonstrated to arrive at a design solution.

- *Providing a theoratical framework in the form of design drivers, an evaluation diagram and ergonomic manual*

- *Providing multiple design variants based on the design concepts.*

- *Integrating product visuals into existing locations to demonstrate architectural implementation potential.*

- *Delivering a report and presentation with fundamental knowledge and concepts that recommend further research directions.*

The boundary conditions primarily focus on building technology, the timeframe, and the moment when the research is conducted. This topic could find its optimization in the technical domain within the spectrum of mechanical engineering, where the design interface may be more oriented towards industrial design. However, the most crucial aspect to make the principle work is to transform it into an integrated building product suitable for the built environment. Therefore, the focus remains on building technology. Moreover, the research is mainly conducted during the winter and spring, making it unfeasible to actually test an application on participants in terms of the effectiveness of thermal comfort.

1.7 Relevance

This topic is socially relevant as it addresses the pressing need to reduce CO2 emissions in the built environment and the higher well-being of people in office environments.By exploring energy-efficient climate control systems, the research aims to contribute to significant energy savings and company savings. Additionally, it is socially pertinent as it offers individuals the potential to exert more control over their thermal comfort in office settings, promoting a more pleasant and productive work environment.

Scientifically, investigating the creation of a building product for thermal comfort without impeding other functions is pertinent. There has been minimal research into the experiences and especially the expectations of end users regarding such a device to regulate their comfort in such an environment. By mapping this out, designers are able to effectively design something that meets the requirements of its end users. This aligns with recommendations in the academic world regarding thermal comfort, emphasizing the effectiveness of adaptive capabilities of building components. It explores the possibility of new building products meeting these criteria.

02

LITERATURE REVIEW

2. Literature Review

From a wealth of literature, it is well-documented that people are highly dissatisfied with the indoor climate in open-plan offices. According to Leesman (2023), temperature is the second worst factor regarding office dissatisfaction, with only 31% of individuals satisfied and 61% dissatisfied. But why are people so unhappy with the temperature?

In all current standards and guidelines, both for free-running buildings and HVAC-equipped buildings, adaptive temperature ranges—formed by adaptive temperature limits—are presented as a means to evaluate realised indoor temperatures, rather than enabling adaptive temperature regulation. Instead, heating and cooling setpoints are often still fixed throughout the year, for instance, 21°C for heating and 24°C for cooling. Furthermore, the current formulations based on classes in standards and guidelines result in a "performance class" of a building based on the general idea of "the closer to the (assumed) optimum, the better," an idea that does not lead to the desired outcome of improved comfort (Arens et al. 2010).

Adaptive thermal comfort emphasizes the importance of adjustments. This concept revolves around not maintaining a constant indoor climatological situation but the ability to adapt to different environmental conditions. This principle assumes that people can adapt to the ambient temperature by employing various strategies, such as adjusting clothing, opening a window, or modifying activity levels. Richard and Brager (1998) identify three components: behavioural adjustments (personal, technical, and cultural), psychological adjustments (such as habituation and expectations), and physiological adjustments (genetic adaptation and acclimatization).

Control over one's own situation is thus key in this context to remain comfortable. But what does it do to productivity? Research by, among others, Veitch & Gifford (1996) has revealed the effects of decision control over lighting conditions in a laboratory setting. An interesting conclusion was drawn regarding performance effects on creativity. Specifically, participants who had control over their lighting situation took 15% more time than others.

More studies confirm that control by occupants comes at the expense of workers' effectiveness. Boerstra (2016) also tested this in the areas of temperature, airflow, and ventilation. When there is access to personal control, people make more use of it and are satisfied. However, it was found that this comes at the cost of productivity. They point out that this does not automatically mean that adjustable thermostats, fans, and/or personal climate control systems should not be installed. It is said that these should precisely meet the user's requirements, but to date, there is no application that can do this fully or claims to be able to. Zeiler et al. (2013) make an attempt, but it is still under development, involving an entire system.

In terms of air velocity, this was highlighted by Boerstra (2016), as well as by Zhang et al. (2007). 19% of a group of people with access to a portable fan found the air velocity too low. 8% of a group without access found it too low. A portable fan is seen as an emergency measure.

There seems to be a complex balance between user satisfaction and user productivity. When people have control, they are satisfied but may potentially sacrifice their productivity because they are more preoccupied with it. However, when they have no control over their thermal situation and it is not to their liking, their productivity will further decline.

The positive effects of control are well known, but what exactly is this control, and what kind of control are we discussing? The following sections will delve further into this.

2.1 Perceived Control as a Conceptual Approach

In this context, when discussing control, it refers to perceived control. Perceived control is the belief in one's ability to influence events and outcomes in certain situations. At the bottom of the page, the three domains in which perceived control occurs, as proposed by Bandura (1986), are visible. Control takes place within a specific environment (physical and social environments), then moves through the perception domain (the person's state, both cognitive and biological). If the individual is satisfied, it does not result in specific behaviour. However, if there are opportunities for control and the individual is dissatisfied, it can lead to particular behaviours, which is the third domain.

Before delving into the detailed structure of the model and the interconnections within it, the following page presents an expanded model indicating the relationships, based on Hellwig (2015).

Starting with the environment: this mainly consists of the building context and social context. Since a part of this research involves developing a personal environmental control system, it is included in the environment to clarify where the designer operates. The building context primarily concerns the façade, current systems, and space layout, while the social environment pertains to the organisation, the type of work, and the culture, including clothing protocols. This environment is thus determined partly by its users but primarily by the people who built, designed, or manage the building.

The perception domain is where the user makes the assessment. The user is stimulated and receives certain stimuli from the environment. Subsequently, the process moves to the person's state, which is based on the user's experiences. These experiences are closely linked to the locus of control, which, in turn, is connected to the knowledge of existing control mechanisms. This can vary from one region to another. In conjunction with expectations, this forms the perceived control. From there, the user's actual preference is determined and evaluated.

It is important to note that both environments are linked to constraints. These constraints ultimately form the specific constraints that are linked to the available control. This ultimately determines which exercised control takes place.

To fully understand these constraints, it is necessary to comprehend the elements linked to them. Therefore, the focus is on the perception and environmental areas to examine what these elements are and what influence they have.

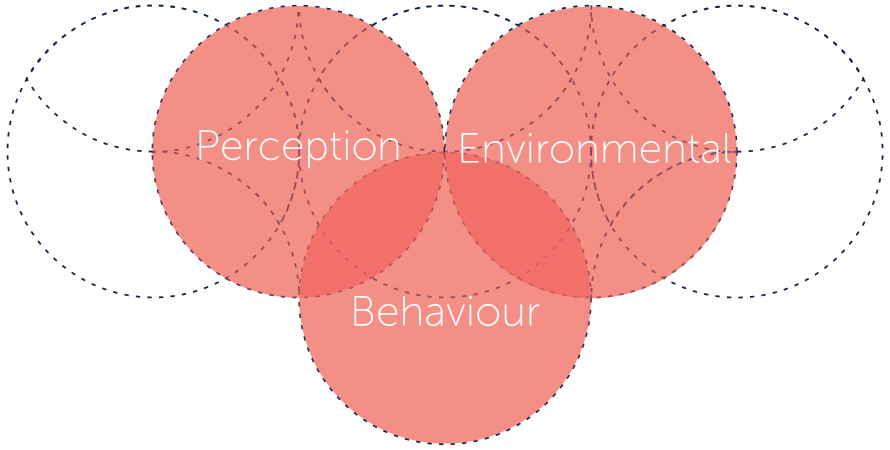


Figure 1: Simplified conceptual model of perceived control

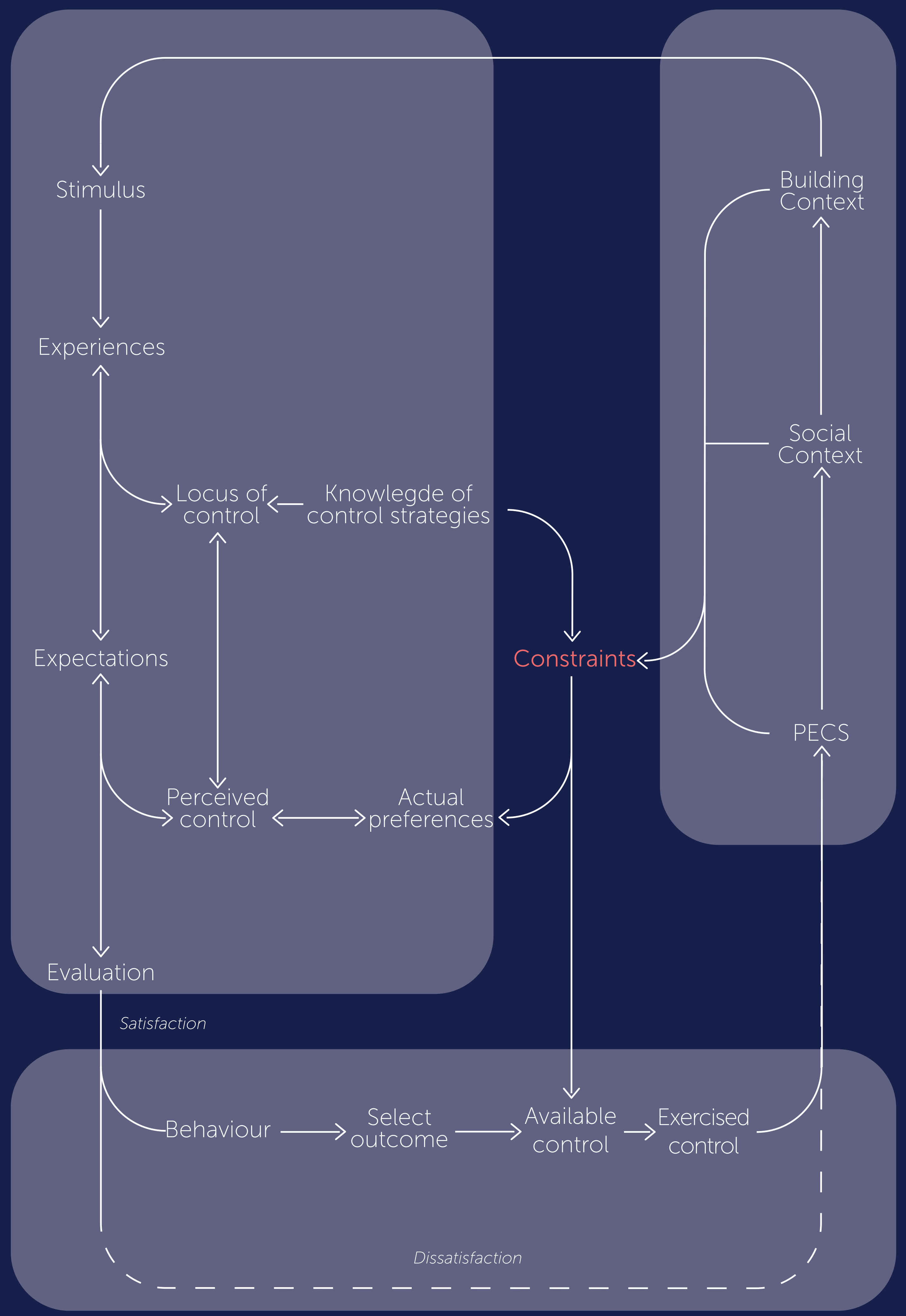


Figure 2: Extended conceptual model of perceived control

2.2 Perceived Control

First, the perception domain is explained, addressing the stimuli, experiences, and expectations. Experiences and expectations are explicitly connected to other elements in the model. Experiences are based on the locus of control in conjunction with existing knowledge of certain control strategies. Expectations are linked to perceived control and actual preferences. These latter factors are directly connected to constraints; knowledge of control strategies and actual preferences are discussed later in the chapter as they can be specifically related to certain criteria. The other elements require further explanation before proceeding.

2.2.1 Stimulus

The stimuli are determined by the quality, intensity, and duration of a particular stimulus. These are the climatic conditions that a person experiences from the environment. It is interesting to discuss these elements in the light of adaptive thermal comfort. Over a longer period, people find a neutral thermal sensation most comfortable because physiological processes work best under these conditions. However, short periods of local heating or cooling can be enjoyable, a phenomenon known as alliesthesia. For example, if the core temperature rises slightly, cooling will be perceived as pleasant. This is called positive alliesthesia. Such cooling would not be perceived as pleasant under normal circumstances. An example of this is experienced on a spring day on the terrace (Kurvers & Leyten, 2022).

In early spring, the temperature is not warm enough to provide a neutral thermal sensation. However, a warm glow from the sun compensates for that and is generally perceived as pleasant. This situation is rated better than an indoor situation where the conditions create a thermally neutral environment (Shimoda et al., 2003). It is important to note that this applies for a short period. Over a longer period, people prefer a thermally neutral environment (Mihara et al., 2022).

If the core temperature deviates too much from the neutral setpoint, positive alliesthesia is desired. This is only possible if there are enough options for the user to adjust the thermal environment, such as opening a window or using an additional fan. It is important that the effects occur quickly. The user must experience the change immediately. This illustrates the difference between opening a window (quickly) and adjusting the room temperature (slowly) (Li et al., 2023).

The downside of perfectly regulated climatic conditions within buildings is the occurrence of thermal boredom. There is still a perception among many people that when everything falls within narrow boundaries indoors, people are most comfortable and therefore healthiest. The opposite appears to be true, as in hybrid buildings where temperature boundaries vary more, this has a healthy effect on people. After all, people are naturally accustomed to fluctuations in the surrounding climate (Parkinson & De Dear, 2014; Arens et al., 2010).

2.2.2 Locus of control

There are many theories and models about control. Before delving into the model used in this research, some context is provided on how other researchers have arrived at this model. An important element of control is behaviour. There are two types of options within this: the individual with their experiences and the environment that the individual is responsive to and behaving in. This is also referred to as the 'locus of control' (Rotter, 1966). Essentially, this is a concept of expectation for control of behavioural outcomes. There are primarily two groups within this concept. Individuals with a strong internal locus of control believe that they are responsible for the behavioural outcome themselves, regardless of success or failure. Individuals with a strong external locus of control believe that the outcome or behaviour is controlled by luck or by others.

Individuals with a more external locus of control tend to hold back in situations where they do not feel they can change them. This can lead to negative associations and perpetuate low expectations; the self-fulfilling prophecy. They may be reluctant to make efforts to change their situation, believing it is destined to fail anyway.

2.2.3 Primairy en cecondary control

Johsen (1974) actually discusses four stages that determine outcome selection control:

1. Outcome selection control process: where one seeks a desirable outcome chosen from multiple possible outcomes.
2. Control of behavior selection: from various behavioral strategies, one type of behavior is selected and applied to achieve the desired outcome.
3. Outcome effectiveness: to reach the desired outcome.
4. Outcome realization or control: receiving and evaluating the outcomes, which are subjective.

The key is that everyone who has control/makes a choice is based on one of these four elements. Above these four elements, there are two other elements. It depends on whether these choices are primary or secondary. This refers to how quickly the outcome is achieved. Johnsen identifies that for primary control, such as controlling a thermostat oneself, while secondary control involves taking action to ask the central building management to change the thermostat settings. Additionally, it is important to consider the number of options. Choice overload can be demotivating and hinder taking control at all.

2.2.4 Perceived control

While Johsen primarily discusses different stages of control that one goes through, Paciuk (1990) focuses on the three options of control:

1. Available control
2. Exercise control
3. Perceived control

Available control pertains not only to the actual buttons but also norms such as dress codes or, for example, manipulation of buttons by central facility management. Exercise control is the control that involves taking action. All these actions essentially fall under one stage of Johsen's framework. You see what is possible, which fits into a certain stage, and then you execute it. However, there's an additional aspect here: perceived control. Paciuk (1990) defines perceived control as a combination of both, involving knowledge of existing available controls in conjunction with the effectiveness of exercise control. Perceived control refers to the individual's sense of control over a situation or environment, regardless of whether that control is actually present.

Perceived control is related to effectiveness. Bordass and Leaman (1997) divide it into three components:

1. Actual control, including the building's location and use.
2. Fine-tuning capability, encompassing not only buttons but also clothing protocols.
3. Speed of response, not only for the user but also for central building management.

Boerstra (2016) categorises perceived control into three distinct levels: not possible, possible but ineffective, and possible. In elucidating this framework, Boerstra employs the term "perceived effectiveness of control." He underscores the significance of several factors, including situational considerations, habituation, memory integration, and expectation effects. This underscores the paramount importance of comprehending the contextual nuances within which one operates. The ensuing paragraph will delve further into this facet of the model.

2.3 Thermal Environment

In this section concerning the environmental aspects of thermal comfort, both the building and social contexts of buildings are discussed, focusing on the parameters influencing thermal comfort. Some of these parameters pertain to the architectural context, while others are attributed to the social context.

Before delving deeper into these factors, the human body's heat balance is first elucidated, forming the basis for understanding thermal comfort. Various forms of heat transfer are discussed in this explanation, including conduction, convection, radiation, and evaporation. Particularly in summer situations, increased air velocity proves effective in aiding the removal of excess body heat. The chapter also highlights which parts of the body can be most effectively cooled.

Initially, the architectural context is addressed, which determines the environmental conditions within a building. Factors such as ambient temperature, radiant temperature, and humidity play crucial roles here. These factors are influenced by both the climatic conditions outside the building and the architectural norms and standards applicable within it. Understanding these aspects is essential to managing thermal comfort within a building.

Subsequently, a deeper examination of the social context ensues. This context pertains to the activities occurring within the building and the clothing protocols required. In an office environment, the level of activity can vary significantly, from sedentary work to more physically demanding activities. Additionally, clothing regulations play a significant role in how individuals experience thermal comfort.

Based on this social context, preferences for air velocity under certain circumstances can be determined. Increased air velocity, which receives considerable attention in this section, proves particularly effective in enhancing thermal comfort in warm conditions. This increased air velocity is often related to personal preferences and is implemented in Personal Environmental Control Systems (PECS), designed to optimize individual comfort.

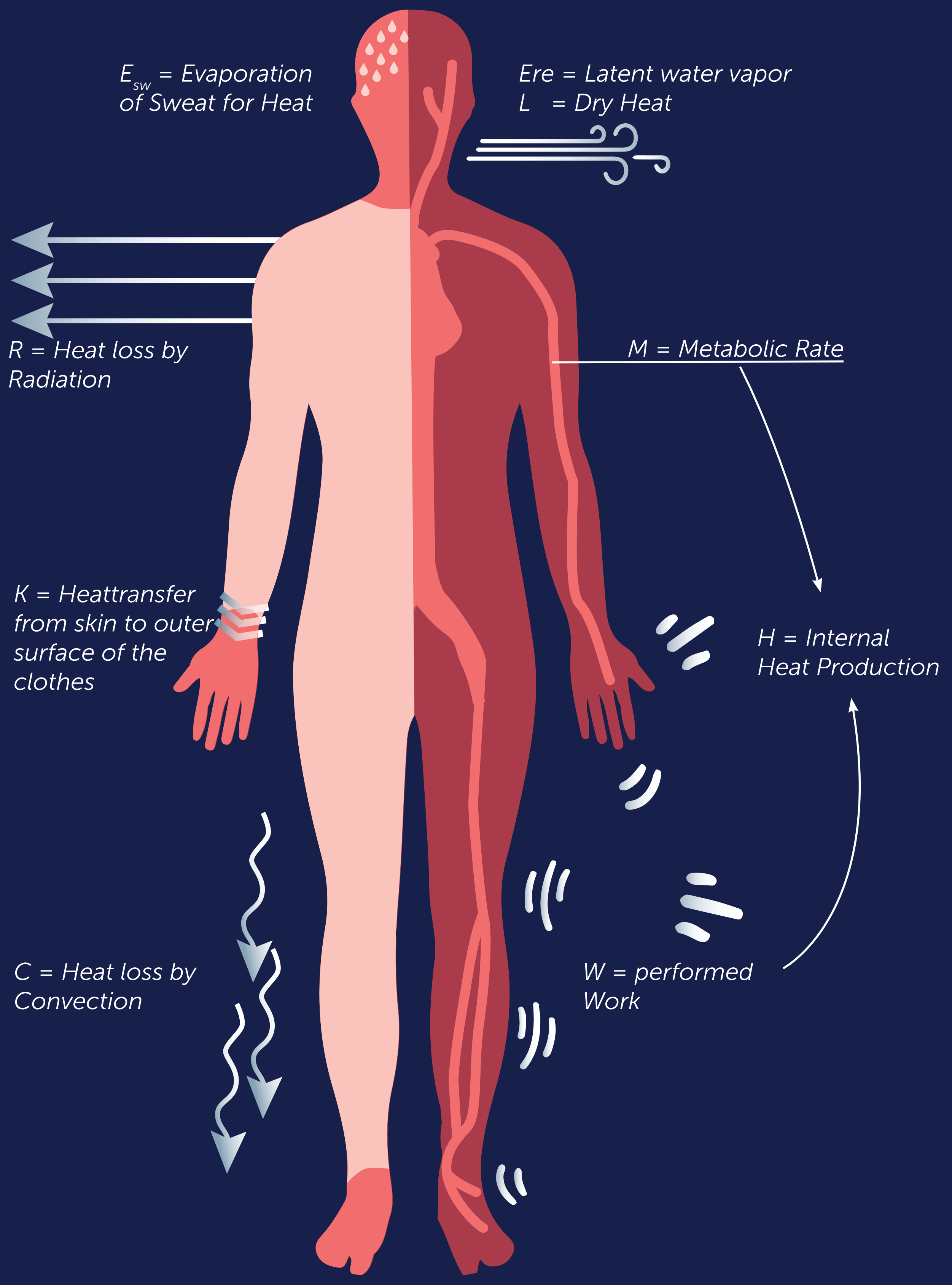


Figure 3 : Heat Balance of the Human Body

2.3.1 Heat balance of the human body

Thermal comfort is described by ANSI (American National Standards Institute)/ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) as:

> “That state of mind that expresses satisfaction with the thermal environment” (2017).

The body can essentially be considered a thermodynamic system that utilizes food and oxygen as energy, maintaining a relatively constant temperature of 37±0.5°C. The stability of this temperature is ensured by the skin, regulating blood flow, sweating, and shivering (Liu et al., 2020). To achieve this, the body’s heat generation must be balanced with what it loses to its surroundings (Butera, 1998). Therefore, it can be said to involve a balance between the body and its environment (see Formula 1).

$$H - E_d - E_{sw} - Er_e - L = K = R + C \qquad (1)$$

The energy is generated by the body’s metabolism and internal heat production (H). Together, these are referred to as the metabolic rate (M). Another factor is the work performed (W), contributing to the body’s heat production. Additionally, there are four factors leading to energy loss through evaporation and respiration. Water vapor moves through the skin as part of the heat regulation system (Ed), where the water vapor is brought forward by sweating, which then has the ability to evaporate (Esw). Sweating is controlled primarily by the temperature of the brain in combination with the skin temperature (Smith & Johnson, 2016). Through breathing, heat is lost in the form of water vapor (Latent, E_{re}) and dry heat associated with the exhaled air’s temperature (L). 20% of heat loss can be attributed to this (Lumen Learning & OpenStax, n.d.).

In typical scenarios, individuals are clothed, adding three factors to the heat balance. These involve three heat transfer factors: radiation, radiation, and convection. Heat transfers from the skin to the outer surface of clothing (K). Heat can exit from the outer surface through radiation (R) and convection (C) (Zhang et al., 2021) (Fanger, 1970). Radiation is a significant factor, causing 60% of heat loss. Convective heat loss accounts for 15%, while only 3% is lost through conduction (Lumen Learning & OpenStax, n.d.). In the following paragraphs, some of these factors will be further elucidated to provide insight into the effects of specific elements within the aforementioned factors.

Heat loss by radiation

The loss of heat through radiation occurs between the occupant and their surroundings. Therefore, this phenomenon is based on the Stefan-Boltzmann formula. The formula is as follows:

$$R = A_{eff}\, \varepsilon\, \sigma\, (t_{cl}^{4} - t_{mrt}^{4}) \qquad (2)$$

A_{eff} is the effective radiation area of the clothed body. ε is the emissivity of the outer surface of the body, a value between 0 and 1, typically ranging from 0.95 to 0.97. σ is the Stefan-Boltzmann constant. Once again, the last terms in the formula are the most interesting. It relates to the temperature difference of the radiating object. T_{cl} is the person, where T_{mrt} is the mean radiant temperature (Fanger, 1970). A small difference in this temperature has a significant impact on the final heat loss because it is raised to the power of 4.

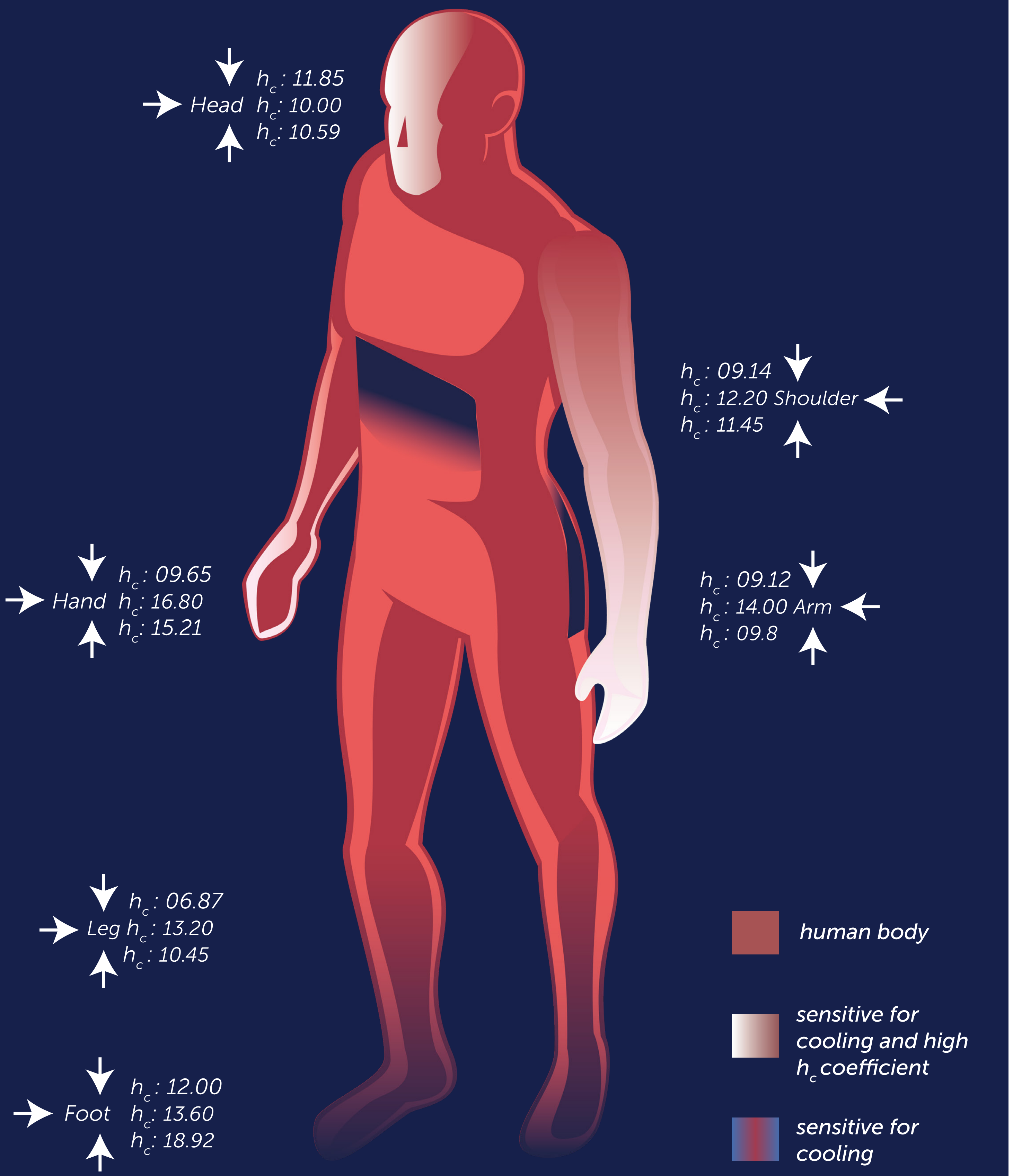


Figure 4 :Body parts with a high convective heat transfer coefficient combined with parts of the body that are sensitive to cooling

Heat Loss by convection

The formula for heat loss by convection is as follows:

(3) $C = Adu\ fcl\ hc\ (tcl - ta)$

Once again, A_{du} indicates that it is expressed per body surface area. fcl represents the ratio between the covered and uncovered parts of the body, essentially the clothing factor. For example, if this factor is 0.7, it means that 70% of the body is covered with clothing. Here, the influence of convection is different. T_{cl} is the temperature of the clothing, with ta being the ambient temperature, unlike radiative heat transfer, which uses the radiant ambient temperature. In this context, the convective heat transfer, h_c, is particularly interesting. It depends on the velocity of air (Fanger, 1970). This coefficient is still tested in various situations today.

Fanger considers the body as a whole, resulting in a single value. However, studies by Gao et al. (2019) and De Dear et al. (1997) have shown significant variations in this coefficient for different body parts. A larger coefficient implies it is easier to remove heat from the body through convection. Gao et al. (2019) also examined whether the direction of velocity concerning the body matters.

The research particularly highlighted six body parts that has notable convective heat transfer coefficients: head, shoulder, arm, hand, leg, and foot. At 1 m/s, the head showed an average high coefficient of 12.4 $W/m^2 \cdot K$. Moving from the head to the fingers, the coefficient increases, creating a greater difference depending on the wind direction. The shoulder has the highest coefficient when the wind comes from above or the side (12.2 $W/m^2 \cdot K$). For the arm, there is a significant difference between horizontal (14 $W/m^2 \cdot K$) and from above and below (10 $W/m^2 \cdot K$).

There is also a great deal of variation in the legs. When oriented horizontally, the leg has the highest coefficient (13.2 $W/m^2 \cdot K$). It's interesting to note that when air comes from below, the foot cools at 18.92 $W/m^2 \cdot K$. In summary, the coefficient of a vertical airflow is higher (11.3 $W/m^2 \cdot K$) than that of airflow coming from above and below (9.18 $W/m^2 \cdot K$).

However, this does not necessarily mean that these are the areas most effective to cool. It only indicates how easily heat can be removed from certain parts of the body with a specific wind. The key is to identify which areas are sensitive to temperature changes in order to alter a particular thermal sensation. Luo et al. (2020) mapped this sensitivity, revealing that the head, arms, hands (especially the upper part), abdomen, and buttocks are highly thermal-sensitive. Interestingly, the feet, lower legs, and upper chest are relatively 2 to 3 times less sensitive than other parts of the body.

Having a high convective heat transfer coefficient does not directly imply that these areas are the most influential in thermal perception. Feet, in particular, seem to represent two extremes in both studies. While feet cool down quickly, their impact on thermal sensation may be less critical than, for instance, the head. An illustrative example of this is the difference between wearing socks in summer and winter. Socks provide insulation, helping to retain warmth, which is crucial as the feet are farther from the central part of the body. The same applies to dissipating heat by putting your feet in a basin of cold water, for instance. The feet act as extensions of your insulating layer, with the center of warmth located at the chest/head. This is also the difference compared to the arms in relation to the feet. The feet are further away from this central part than the arms. The perception of cooling, as previously mentioned in the heat balance of the human body, depends not only on actual heat loss, where skin temperature plays a significant role, but also on the temperature of the brain. Your arms and head are closer to the brain, so cooling is transmitted more quickly than with your feet.

Therefore, the head and arms play a larger role in the perception of thermal comfort (Olesen, 2020).

Internal heat production

The internal heat production plus the work performed together constitute metabolism.

(4) $M = H + W$

Metabolism is expressed in kcal/hr, representing the amount of heat required to raise one kilogram of water by one degree. The external mechanical efficiency formula is as follows.

(5) $\eta = W/M$

Combine the above formulas and express them per unit body surface. This results in the equation as seen in (5).

(6) $H/A_{du} = M/Adu\ (1 - \eta)$

The unit of H/Adu is now kcal/hr m^2 (Fanger, 1970). These formulas are not meant for individual calculations but to provide insight into the relationship between different elements to derive a unit commonly used in thermal comfort.

Heat loss by skin diffusion

Water vapor diffusion through the skin is a form of (unconscious) transpiration. This process is not part of thermoregulatory control. It is more of a passive process that doesn’t necessarily depend on the body’s temperature but rather on physical environmental factors such as humidity and temperature. The formula for water vapor diffusion is:

(7) $Ed = \lambda\ m\ A_{du}\ (p_s - p_a)$

Here, λ is a constant (575 kcal/kg) representing the heat of vaporization of water. m is the permeance coefficient of the skin, which is 6.1 * 10-4 kg/hr m^2 mmHg. Similar to other formulas, A_{du} indicates that it is a unit per body surface area (Fanger, 1970). The explanation of the formula is mainly related to the units of p_s and p_a. p_s represents the saturated vapor pressure at the skin temperature, and p_a is the vapor pressure of water vapor in the ambient air, both in mmHg. p_s refers to the maximum amount of water vapor the air can hold at the skin temperature. As the temperature increases, this factor also increases, but exponentially (Legg, 2017). As the temperature rises, p_a also increases, but in a linear fashion (Ortiz-Prado et al., 2019). The ratio of p_s to p_a is different. This is the reason why, at the same air temperature, people may experience comfort differently in a humid climate than in a drier climate. Sweating is effective for cooling your body, but when humidity is high, the air is already saturated, making it difficult to release the heat trapped in the sweat to the surrounding air.

Heat conduction through clothing

What actually happens here is that dry air moves from the skin to the outer layer of clothing. Because all forms of heat transfer are involved (Radiation, Convection, and Conduction), calculating this is quite complex. Gagge et al. (1941) introduced a simplified version that defines the total thermal resistance with a dimensionless value:

(8) $I_{clo} = R_{cl}/0.18$

Iclo is measured in clo units. The dry heat transfer formula can be expressed as follows:

(9) $K = A_{Du} * (t_s - t_{cl})/0.18\ I_{cl}$

Here, Ts is the skin temperature, and tcl is the temperature of the clothing. Adu simply indicates that we are once again discussing body surface areas.

2.3.2 Thermal comfort parameters

In the above paragraphs, the heat balance of the human body has been briefly discussed. These are not the direct factors engineers use to determine the thermal comfort of individuals. Globally, the Fanger Thermal Comfort model, developed by Povl Ole Fanger, serves as the basis for this purpose.

Six parameters are central to the model:

- Ambient temperature (°C): The air temperature in the environment.
- Radiant temperature (°C): The temperature of the surrounding surfaces.
- Humidity (%): The amount of water vapor in the air.
- Clothing insulation (clo): The thermal insulation of the worn clothing.
- Metabolic rate (met): The body’s heat production due to metabolic processes
- Air velocity (m/s): The speed of the air around the individual.

These factors are used to determine the average thermal sensation assessment of a group of people. This is the Predicted Mean Vote (PMV), with its counterpart being the Predicted Percentage of Dissatisfied (PPD), indicating the percentage of users dissatisfied with their thermal comfort. This forms the basis for many current standards (ISO 7730, ASHRAE 55).

To determine the appropriate air velocities people should receive in the summer in a temperate maritime climate, it is important to ascertain the values of the other parameters. This clarifies which air velocities the device should generate and also reveals the constraints under which this project is being executed.

2.3.3 PMV & PPD

In figure 5, the relationship can be observed between the group of people rating their thermal sensation between -3 and 3. From there, it can be determined what percentage of individuals are dissatisfied. In this model, it is assumed that a neutral state (PMV=0) is the state in which people would prefer to be, thinking that this state would have the lowest number of dissatisfied individuals with their thermal comfort.

However, research by Humphreys and Hancock (2007) and others reveals that this assumption is not necessarily true. The state in which people want to be is not necessarily neutral. The data confirm that the desired experience on the ASHRAE scale often deviates from ‘neutral’ and systematically varies from person to person. Individuals had diverse preferences regarding their thermal comfort. Another study (Humphreys et al., 2015) indicates that preferred thermal sensation increases as the room temperature rises. The warmer it is outside, the more people accept that it is warmer inside (De Dear & Kim, 2016). The outdoor temperature is then compared to the (comfort) temperature indoors.
The PMV and PPD serve as a good starting point to assess how users feel in buildings, but there are additional factors that determine when people feel comfortable or uncomfortable in a building.

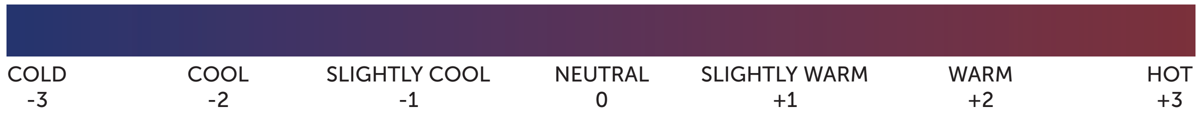
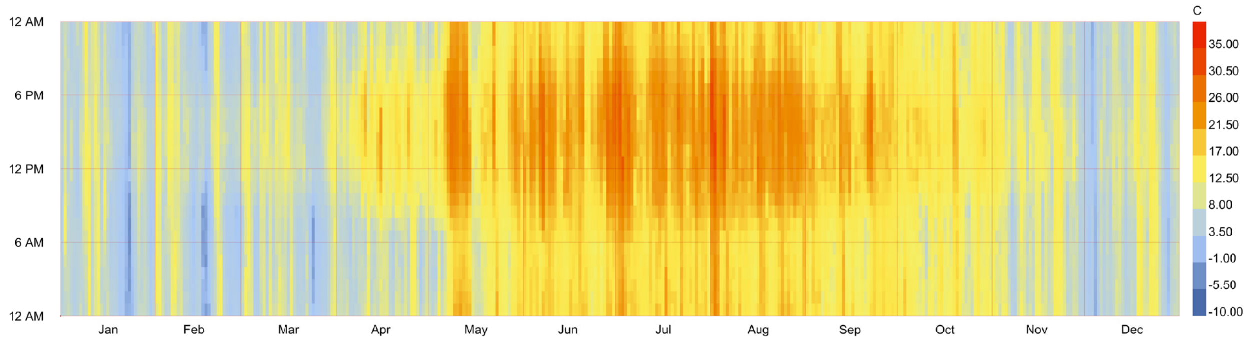


Figure 5: 7 points scale of the Predicted Mean Vote



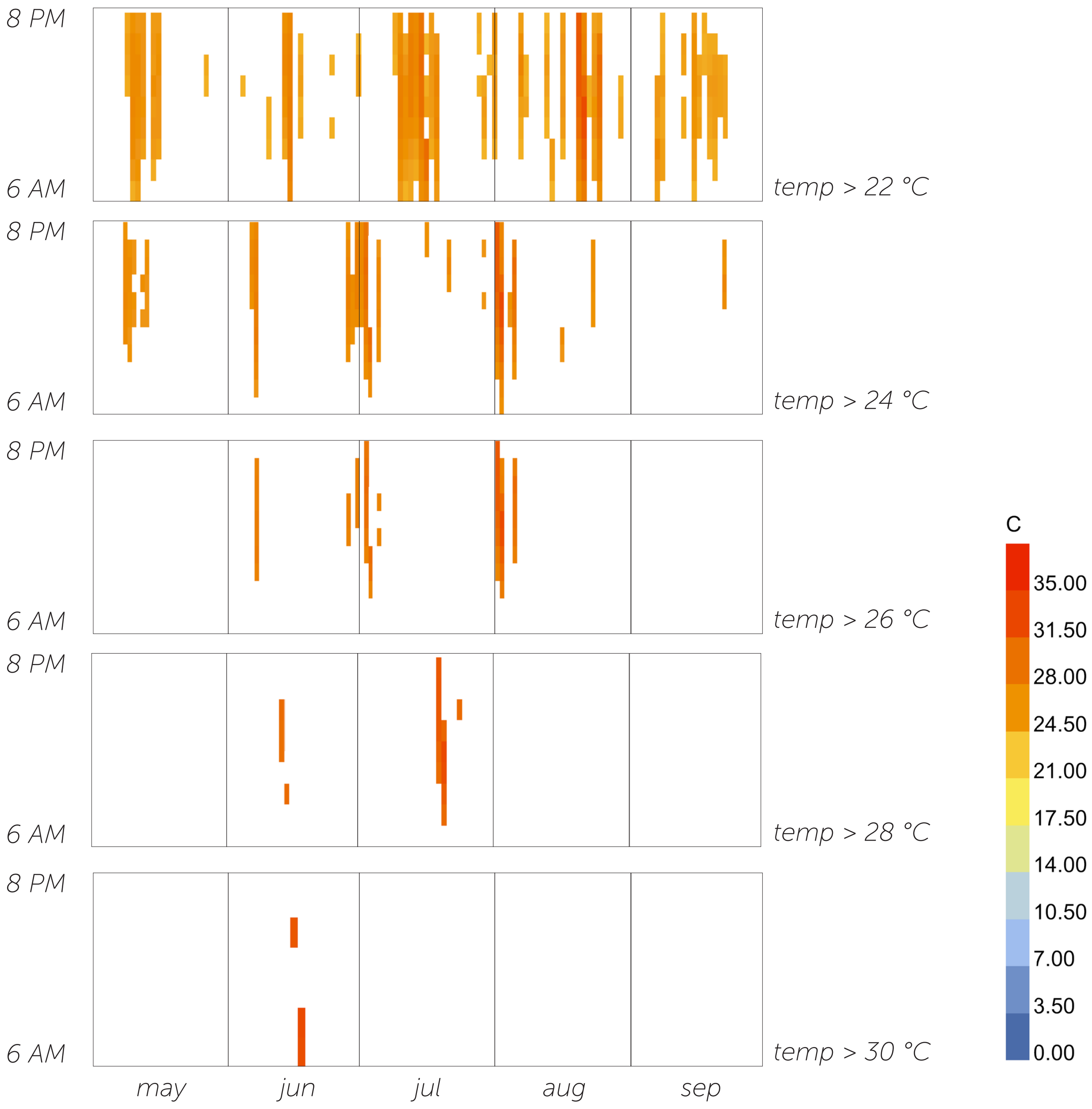


Figure 6: Dry Bulb Temperature (°C), Amsterdam (IWEC Data)

2.3.4 Ambient temperature & radiant temperature

The two fundamental temperatures in the Fanger model are the Ambient Temperature (T_a) and the Mean Radiant Temperature (T_{mrt}) . The T_a is the temperature measured in the air. The T_{mrt} takes into account the radiation exchange between a surface and the human body. In thermal comfort models, the Operative Temperature (T_o) is often used. This is the average temperature at which a person exchanges heat with their surroundings, considering both convection and radiation.

(10) $$T_o = (h_r T_{mrt} + h_c T_a) / h_r + h_c$$

As can be seen, the radiant and convective heat transfer coefficients are included here. These have been discussed for each body part in the paragraphs above. For the human body, the radiant heat transfer coefficient (h_r) is 4.5 $W/m^2·K$, and for the convective heat transfer coefficient (h_c) , it is 3.4 W/m^2 when seated and 3.3 when standing (De Dear et al., 1997b).

There is also another formula for the operative temperature based on the T_{mrt} and T_a, combined with the air velocity.

(11) $$T_o = (T_{mrt} + (T_a \sqrt{10v}))/ 1 + \sqrt{10v}$$

The elements that are dominant will determine how these formulas are used. For instance, T_{mrt} and T_a are the same and the T_o is the same if they are equal when v is less than 0.1 m/s.

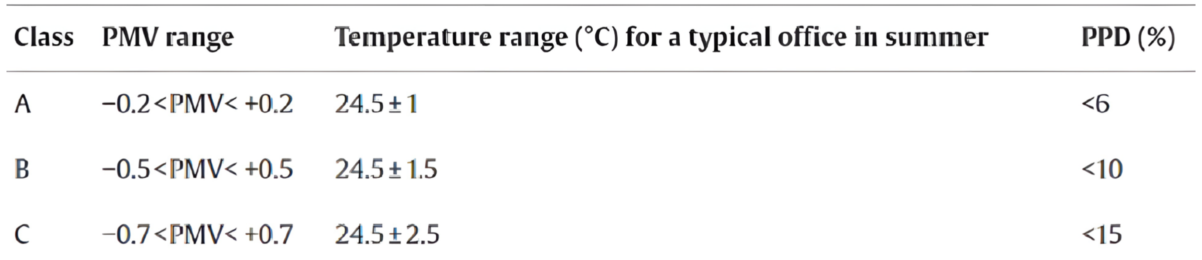
There is a significant difference between T_a and T_{mrt} especially when a space has windows facing southeast and southwest. Radiation is much more dominant in such cases, leading to a completely different experience of the T_o.

The operatieve temperature is also the temperature commonly used in many norms and standards. NEN-EN 16798-1 and ISO 7730 use the operative temperature and have their standards for offices. Often, a distinction is made between upper and lower limits for summer and winter situations. Adaptive guidelines also have a considerable range, taking into account the outdoor temperature. Buildings are becoming more insulated (Ürge-Vorsatz et al., 2015), and the internal heat load of buildings has increased due to the growing number of devices per person (Kim et al., 2018). As a result, it can be warmer inside buildings than outside.

The ISO standard 7730:2005 proposes three categories of thermal comfort: Category A (PMV ±0.2), Category B (PMV ±0.5), and Category C (PMV ±0.7). In NEN-EN 15251:2007 , the same three categories are used (although they are referred to as Class I, II, and III, respectively) for buildings with mechanical climate control. Figure 7 illustrates the temperatures associated with each category.

The left page shows the annual temperatures, with the summer months of June, July, and August being the designated times. It is also included because the weather in May and September is roughly within the same range. The meteorological data comes from Amsterdam, which has a temperate maritime climate. There has been a discernible increase in the overall number of warm days compared to two decades ago. It makes sense to adjust the indoor temperature to match the outside temperature when it's warm. A substantial disparity may result in health problems. This phenomenon also happens, for instance, when people set their home's air conditioning system too cold.

Li et al. (2019) also investigated whether the temperature range specified in the standards is accurate. The new PMV values were compared with standards, and it was concluded that the temperature range could be up to two degrees higher. The maximum was thus 26 °C (Class B), extending to 28 °C. This thesis focuses on increasing local air velocities while potentially raising the overall temperature to achieve potential savings. Therefore, this value is adopted to assess its feasibility.



Class	PMV range	Temperature range (°C) for a typical office in summer	PPD (%)
A	−0.2<PMV< +0.2	24.5 ± 1	<6
B	−0.5<PMV< +0.5	24.5 ± 1.5	<10
C	−0.7<PMV< +0.7	24.5 ± 2.5	<15

Figure 7: ISO standard temperature ranges (ISO7730)

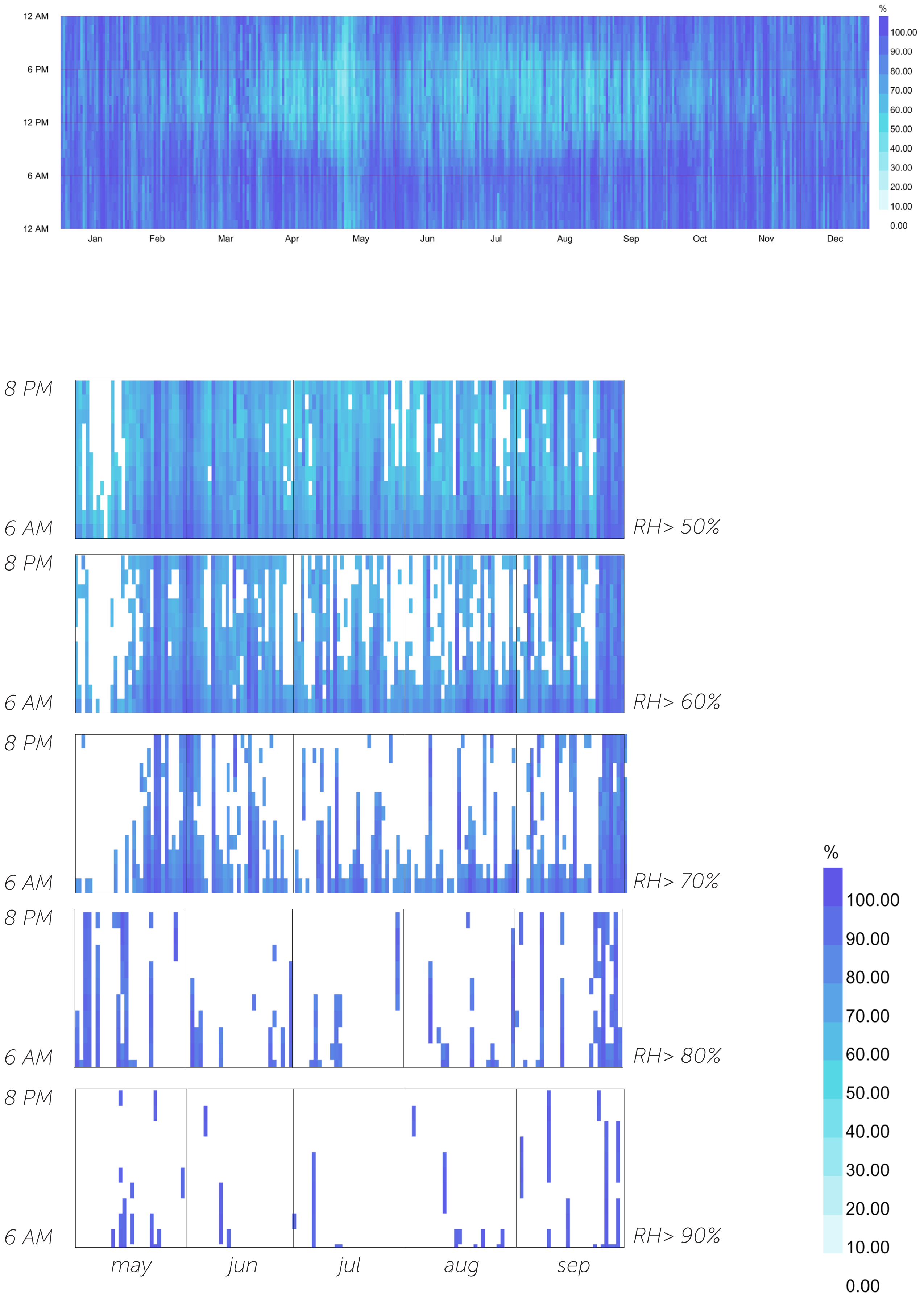


Figure 8: Relative Humidity (%), Amsterdam (IWEC Data)

2.3.5 Relative humidity

Relative humidity is an essential factor that was not explicitly mentioned in many previous studies on increasing airspeed. In a comprehensive study where preferred airspeeds are plotted against certain temperatures, it is noted to be in a 'humid climate' (Yang et al., 2010). The exact relative humidity is not specified. As a reader/researcher/engineer, it is challenging to place this in a comfort table because the data are not as clear. Nowadays, these values are considered more frequently.

Therefore, it is crucial to examine the relative humidity we are dealing with. On pages 34 and 35, the outside temperature and relative humidity are shown. Since this concerns a summer situation, only the months of June, July, and August are considered. As the weather is similar in May and September, these months are also included. Additionally, the hours have been adjusted from 8 am to 6 pm, representing typical office hours. In the previous paragraph, the min and max temperatures in buildings were discussed.

The humidity changes inside a building, even if the air is not conditioned, due to different temperatures often present. The minimum and maximum values of RH are where it is maximally colder outside during office hours in the summer and very warm inside. Of course, the exact indoor temperature relative to the outdoor temperature depends on factors such as insulation, glass facade distribution, and location. However, the aim is to establish a maximum and minimum range. In an extreme case where the outside temperature is 22 °C and the inside temperature is 28 °C with a low humidity of 50% outside, the indoor RH is 34.4%. In the other extreme case where it is 30 °C outside, inside maximum 28 °C, and indoor RH 70%, the indoor RH would be 79.3%. This range is quite large and inconvenient to work with. The most dominant outdoor RH is between 50% and 70%. It certainly happens in the summer that it is more humid outside (approaching 80%). However, from multiple sources, it can be concluded that it often decreases inside buildings (Nguyen & Dockery, 2015).

Of course, this is the range for up to unconditioned buildings. Many buildings are conditioned. Standards can also be considered here. ASHRAE -55 prescribes a range between 30-60% for a healthy indoor climate. Razjouyan et al. (2019) confirms that this would be a healthy range. Another source mentions that 40-60% would be healthier (Wolkoff et al., 2021). Because it concerns temperate maritime climates where it predominantly tends to be more humid, a range between 40% and 70% is established, assuming situations where there are unconditioned buildings, and the relative humidity is not directly controllable.

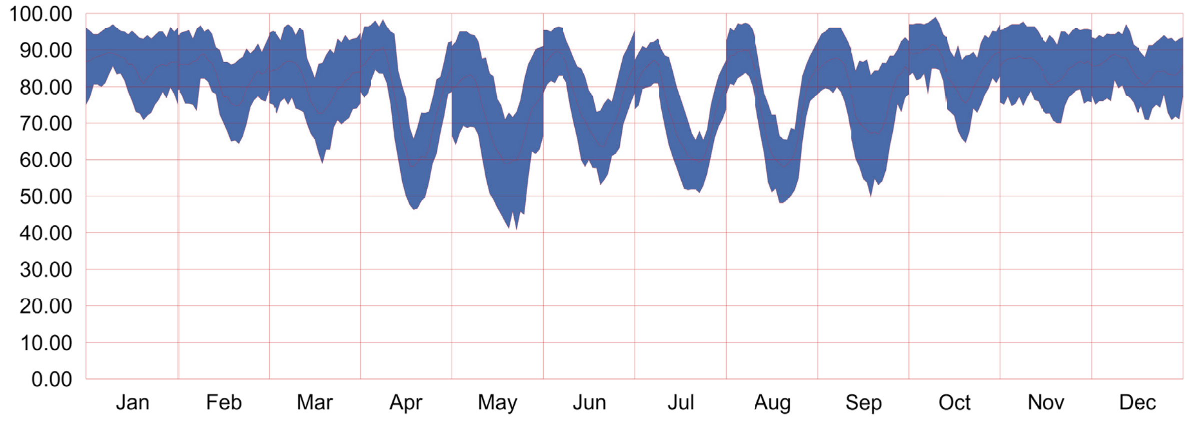


Figure 9: Relative Humidity average per month (%), Amsterdam (IWEC Data)

total **0.48 clo**	total **0.66 clo**	total **0.55 clo**	total **0.50 clo**	total **0.59 clo**
bra **0.01 clo**		bra **0.01 clo**		bra **0.01 clo**
panties **0.03 clo**	men's briefs **0.04 clo**	panties **0.03 clo**	men's briefs **0.04 clo**	panties **0.03 clo**
	T-shirt **0.08 clo**	Camisole **0.08 clo**		Camisole **0.08 clo**
Short sleeves **0.15 clo**	long-sleeve blouse **0.25 clo**	short-sleeve shirtdress **0.29 clo**	polo shirt **0.17 clo**	short-sleeve blouse **0.19 clo**
straight trousers (thin) **0.15 clo**	straight trousers (thin) **0.15clo**		straight trousers (thin) **0.15 clo**	skirt (thin) **0.14 clo**
Ankle-length socks **0.02 clo**	Ankle-length socks **0.02 clo**	panty hose **0.02 clo**	Ankle-length socks **0.02 clo**	panty hose **0.02 clo**
shoes **0.02 clo**	shoes **0.02 clo**	shoes **0.02 clo**	shoes **0.02 clo**	shoes **0.02 clo**
Standard office chair **0.10 clo**	Standard office chair **0.10 clo**	Standard office chair **0.10 clo**	Standard office chair **0.10 clo**	Standard office chair **0.10 clo**

Figure 10: Clothing levels for typical office situations: two possible men's outfits and three possible women's outfits

2.3.6 Clothing insulation

Many offices no longer adhere to a strict dress code. Not everyone wears the same three-piece suit anymore, unless a uniform is required, such as in the police or hospitals. In offices, people tend to dress more casually. However, in a summer situation, not everyone wears shorts and short sleeves to work. Various forums (What Should I Wear? The Ultimate Guide to Workplace Dress Codes, 2023) (Hub, n.d.) explain the importance of dressing appropriately for work. The clo levels from the ASHRAE 55 standard are used because they are more specific for each garment compared to ISO 7730:2005. However, the value for short sleeves is derived from ISO 7730.

In figure 10, three clothing options for women and two for men are presented. Multiple variations are possible, but it provides an idea of lighter and heavier clothing options for maintaining a formal appearance at work. Additionally, research by Morgan and De Dear (2003) indicates a correlation between outdoor weather and how people dress. People do adjust their clothing based on the current weather or weather forecasts.

This does not imply that estimating thermal comfort in a summer situation regarding clothing level is straightforward. There is a significant difference of 28% between the heaviest clothing level for men (0.66 clo) and the lightest clothing level for women (0.48 clo). This range should be taken seriously in simulations to assess its potential impact.

2.3.7 Metabolic rate

In the ASHRAE 55 standards, the range for office work is considered to be between 1.0 and 1.4 MET (55-80 W/m2). This applies to seated office work where individuals read or engage in activities at a desk. Standing desks have become more prevalent (MacEwen et al., 2015), and it's noted that activity has a greater impact on metabolism than posture. There was a belief that there would be a significant difference between sitting and standing, and while this difference exists, it is acknowledged in the standards. However, the contrast between sitting and standing is greater than between standing and walking. Various studies have tested these standards, with Zhai et al. (2018) being one example. The conclusion drawn is that the standards slightly overestimate the metabolic rate for both standing and sitting office work. They proposed a value of 1.3 MET for standing office work instead of the standard 1.4 MET. Zhai et al. (2017) confirmed that these activities fall within the specified values of the ASHRAE 55 standards. However, walking activities seem to be slightly underrated compared to the standards (Zhai et al., 2018). The standard assumes 1.7 MET for light walking, but this study found values of 1.8 MET for a 1 km/h walk and 2.5 MET for a 3 km/h walk, while the standard suggests 2.0 MET. While this research may not necessarily lead to changes in the standards, it indicates that if this thesis adopts values between 1.0 and 1.3 MET, it aligns with the findings. If the focus shifts to locations where people are more actively moving around, there might be a consideration to use slightly higher values than the current standards suggest.

All parameters essential for selecting the appropriate airspeed are now known. As a starting point, the operative temperature is considered to increase from 26 to 28 degrees Celsius. Therefore, these temperatures are important to maintain at a minimum. Additionally, a humidity range between 40 and 70% is being considered. For clothing insulation level, a value of 0.5 to 0.6 clo is chosen, as many offices still require formal attire. This applies to both sitting and standing office work, with metabolic rates of 1 and 1.4 MET, respectively.

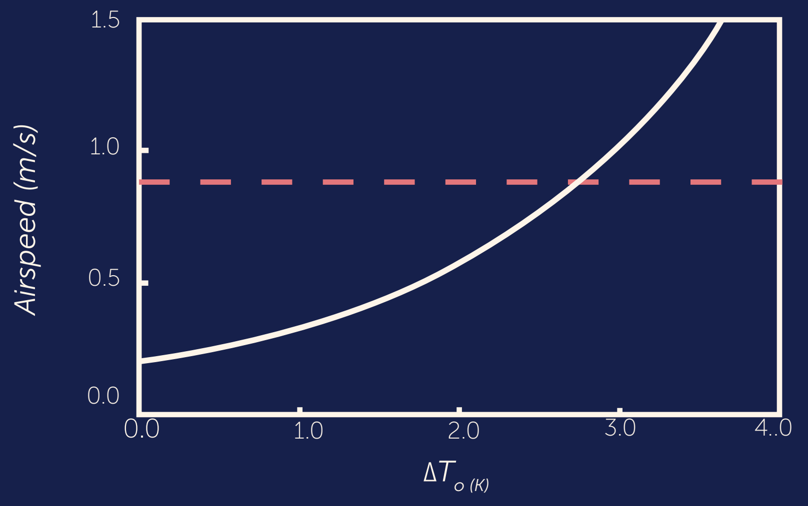


Figure 11: Elevated airspeed in relation to cooling, the red line indicates the maximum wind speed before, for example, paper starts swirling (NEN-EN 16798-1, 2019)

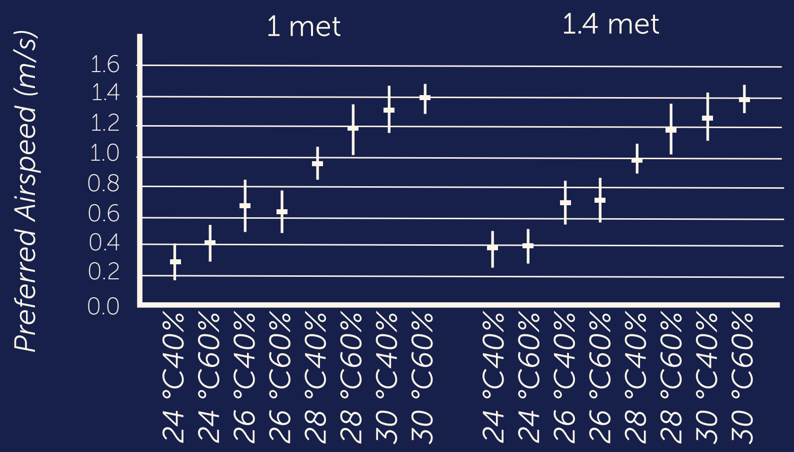


Figure 12: Preferred air speeds each test condition for each fan setting. (Zhai et al., 2017)

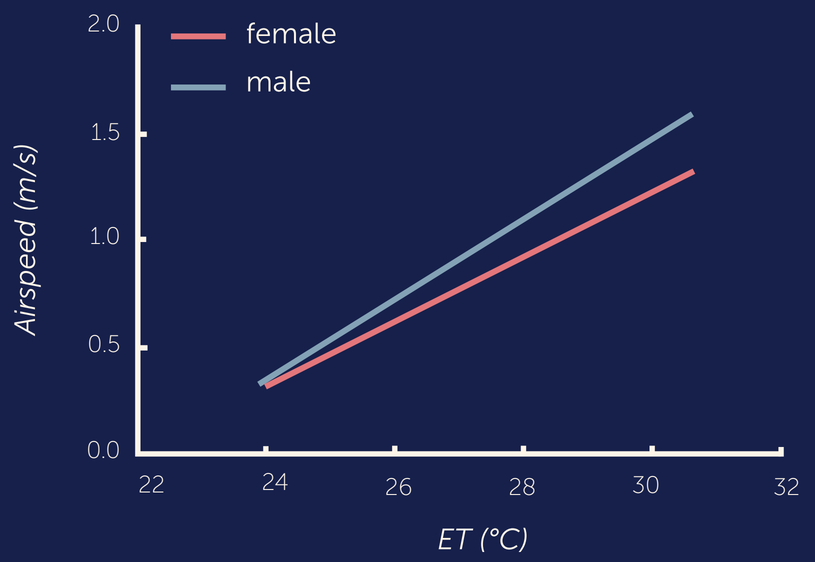


Figure 13: Prefered airspeed under different temperatures for male and female (Zhai et al., 2017)

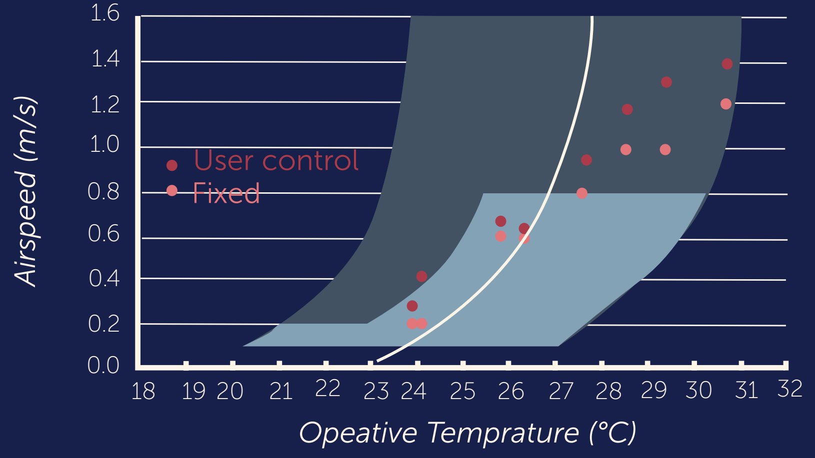


Figure 14: Test results projected onto the ASHRAE-55 standard (Zhai et al., 2017)

2.3.8 Air velocity

For centuries, people have used air velocity to cool themselves. In South Asia, they used what was called a "Pankh," Hindi for wing. It was a square made of strips of bamboo woven together. By waving it, a small breeze was created. During the British colonial regime, a variation called "Punkah" was made by hanging large screens from the ceiling and moving them from the outside using ropes (Devmaster, 2024). Houghten and Yaglou (1924) were already exploring this in the 1920s and 30s of the last century. However, people are very cautious (especially in temperate maritime climates) about working with higher air velocities in buildings. Perhaps because an increase in air velocity in ventilation ducts can generate a lot of noise (Mak, 2002). Another reason could be the fear of drafts, although recent sources indicate that the majority of building occupants prefer more air movement rather than less under higher temperatures (Toftum et al., 2003).

The effect of a higher air velocity is that it promotes heat transfer through convection and evaporation, resulting in a refreshing sensation known as the 'Breeze effect.' Figure 11 (based on NEN-EN16798-1, 2019) illustrates the relationship between airspeed and operative temperature, but also provides a threshold indicating when, for example, papers on desks begin to flutter.

Selecting the right airspeed

The airspeed required for this project depends on the other aforementioned factors. A study by Zhai et al. (2017) aligns well with the described conditions. The metabolic rate (met level) ranged between 1 and 1.4 met, in accordance with ASHRAE 55 standards, and was concurrently measured.

The temperatures ranged from 24 to 30 degrees Celsius, largely consistent with our conditions. The relative humidity during testing ranged from 40% to 60%, and the clothing level was based on 0.5 clo. Twenty-three participants (12 females, 11 males), healthy young individuals, took part in this study. The test examined conditions without a fan, with a fan operating at a fixed airspeed, and with a control airspeed at levels 1 and 1.4, with a maximum airspeed of 1.6 m/s (figure 12).

An interesting observation is the relationship between ET (which can be regarded as operative temperature) and airspeed (figure 13). It reveals two key aspects. Firstly, it serves as an excellent gauge to determine the preferred airspeeds under these conditions at a specific temperature. Additionally, it indicates that women prefer a slightly lower airspeed than men, with the difference becoming more pronounced between 28 and 30 degrees Celsius.

Furthermore, their results are compared with the Percentage Satisfaction model of ASHRAE-55 (figure 14). Their findings align with those of ASHRAE-55. Even above the 0.9 m/s mark, a standard line is visible. One could argue that no control is needed on the left side of the graph. In ASHRAE-55's model, we see a slightly steeper slope of the graph than that of Zhai et al. themselves. This graph clearly shows a correlation with the breeze effect.

In the CBE Berkeley tool, you can also input these data and more or less achieve the same results, especially at operative temperatures of 26 and 28 degrees Celsius. In image 15, where no wind speed is assumed at 26 degrees and standing office work, it falls well outside all classes with a PPD of 17%, whereas with the preferred air velocity from the Zhai study, the PPD is 7%, 10% lower. To allow temperatures to rise within buildings, an operative temperature of 28 degrees Celsius is also interesting to consider. With normal seated office work, you have a PPD of 28%, representing more than a quarter of building occupants, while with an air velocity of 1.2 m/s, dissatisfaction decreases to only 6%.

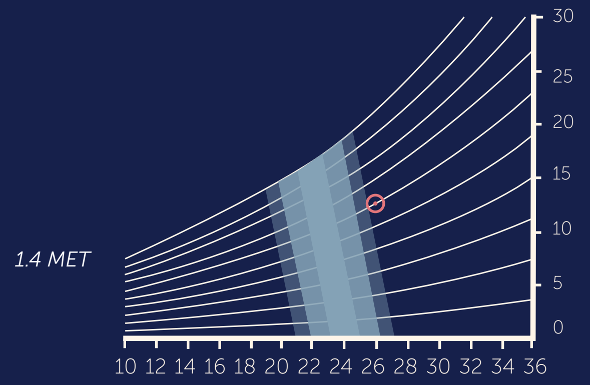


Figure 15: Zhai et al. (2017) measurements implemented in CBE Berkeley tool (26°C, 0.0 m/s, 60%, 0,6 clo, PMV: 0.82) (Zhai et al., 2017)

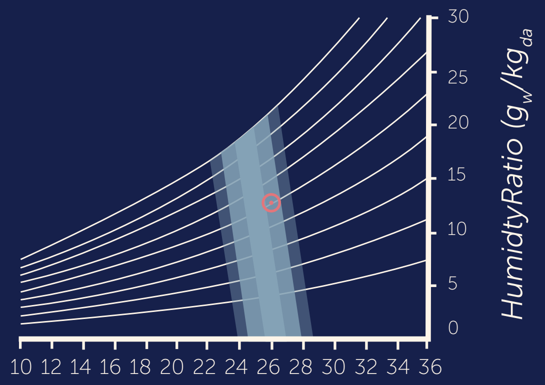


Figure 16: Zhai et al. (2017) measurements implemented in CBE Berkeley tool (26°C, 0.7 m/s, 60%, 0,6 clo, PMV: 0.31) (Zhai et al., 2017)

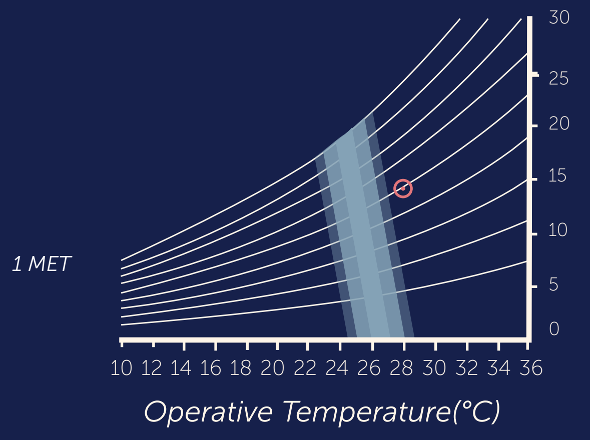


Figure 17: Zhai et al. (2017) measurements implemented in CBE Berkeley tool (28°C, 0.0 m/s, 60%, 0,6 clo, PMV: 1.05) (Zhai et al., 2017)

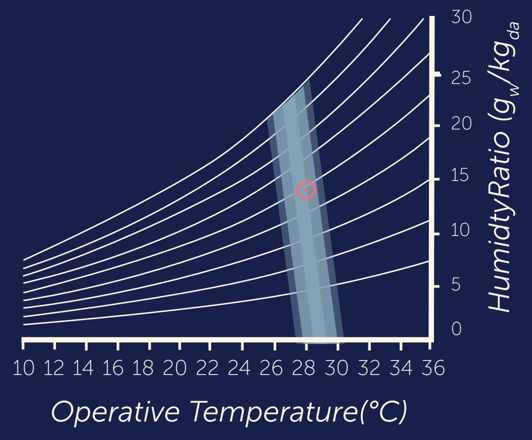


Figure 18: Zhai et al. (2017) measurements implemented in CBE Berkeley tool (28°C, 1.2 m/s, 60%, 0,6 clo, PMV: 0.12) (Zhai et al., 2017)

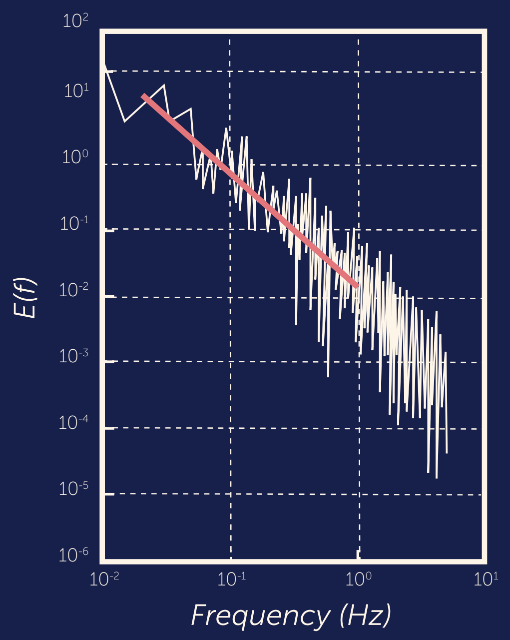


Figure 19: Comfortable natural wind (Zeng et al., 2021)

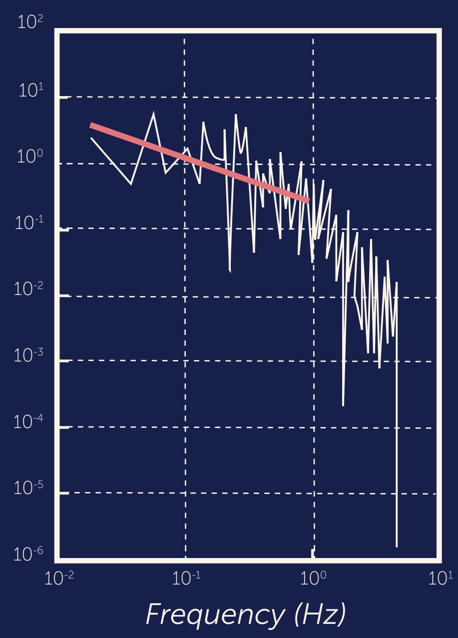


Figure 20: Uncomfortable natural wind (Zeng et al., 2021)

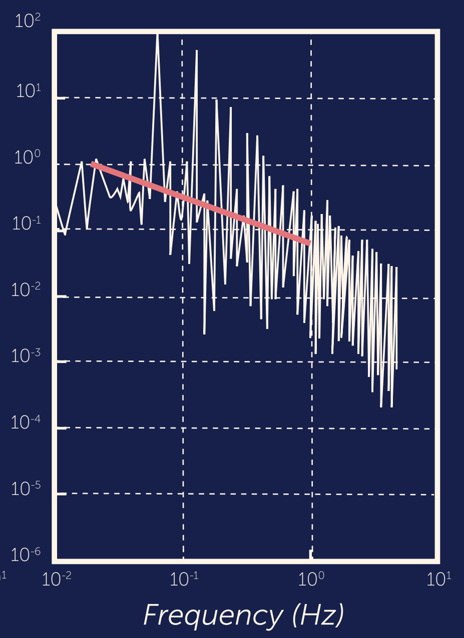


Figure 21: Mechanical wind(Zeng et al., 2021)

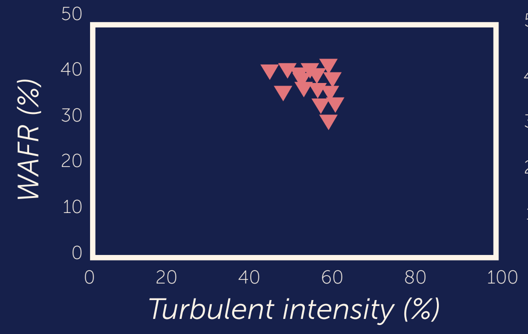


Figure 22: Scatter plots between WAFR and turbuleent intensity of natural wind (Xie et al.,2023)

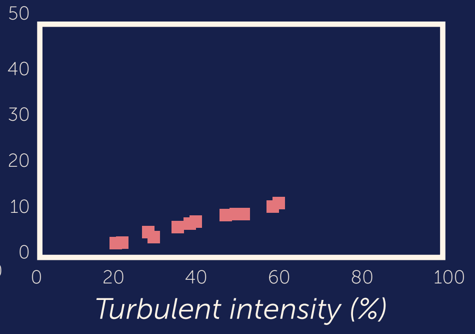


Figure 23 Scatter plots between WAFR and turbuleent intensity of axial fan (Xie et al.,2023)

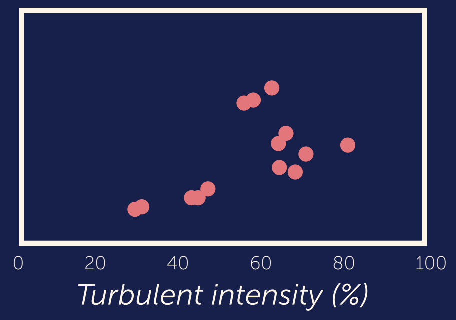


Figure 24: Scatter plots between WAFR and turbuleent intensity of wall airco (Xie et al.,2023)

2.3.9 Draught characteristics
Draught ratio

Draft is often defined as an unwanted local convective cooling of a person (Fanger, 1970). The thermoreceptors in the skin are very sensitive to changes in skin temperature (Khiavi et al., 2019). Draft creates a cooling effect on the skin through convection. Looking solely at temperature, it can be stated that this mainly occurs at air temperatures below 22-23 °C (draft limit 0.15 m/s at 23 °C) (Toftum, 2004). Above this temperature, people often prefer more air velocity than less; even when they feel slightly cool, they still desire that airflow. However, drafts are not solely dependent on the air temperature. it involves more factors. Research by Hara et al. (1997) reveals that people find a natural breeze the most comfortable compared to mechanical wind. This is because wind varies much more than mechanical wind, stimulating different points of the body. This, in turn, has a connection with positive alliesthesia (Xie et al., 2023). The exact factors and differences behind this phenomenon remain unknown to this day. However, certain factors have been identified as significantly different. In the field of thermal comfort, three main factors are considered: airspeed, turbulence intensity, and fluctuation frequencies. Fluctuations in the air refer to broader and more general changes in airflow, while turbulence specifically denotes chaotic, unstable air movements.

Fluctuation frequency

Hara et al. (1997) and Shimizu and Hara (1996) identified the relationship that wind shares the same fluctuations as the human body: 1/f. This aligns with fluctuations in acoustics (Voss & Clarke, 1975) and lighting (Zeng et al., 2021). Numerous studies have explored the frequency of airflow at which people experience the most comfort or discomfort. The challenge lies in determining the temperature conditions under which these tests are conducted. Zhou and Melikov (2002) found that frequencies between 0.2-0.6 Hz were the most uncomfortable. In contrast, Xia et al. (2000) discovered that people found wind most comfortable between 0.3 and 0.5 Hz. The key consideration here is whether increased airspeed is desirable. Huang et al. (2012) compiled various studies, and the frequency range remained relatively broad, spanning from 0.2 to 1 Hz. The ranges presented are quite extensive. A more prominent and distinct difference can be observed in the powerspectrum (Ouyang et al., 2006). This particularly involves the slope difference (β) (Kang et al., 2013). The graphs illustrate that natural wind(figure 19) has a much steeper slope compared to mechanical wind (figure 20). Additionally, Figure 21 indicates that an uncomfortable wind aligns somewhat within the range of mechanical wind.

Turbulent intensities

Turbulence and its characteristics are highly dependent on the environment. Nevertheless, a certain trend can be recognized. Xie et al. (2023) found that natural wind speeds are around 20+- up to 60% (figure 22). The other plots of mechanical ventilation (figures 23,24) also exhibit a pattern related to the direction from which it originates (WAF, Wind Azimuth fluctuation rate). The transient fluctuations, which are perceived as turbulence, often have a period of less than 10 minutes (Julia, 2010).

Something more distinct from turbulence but leaning towards the directional aspect is the finding from Rober et al. (1997) that air from top to bottom tends to resemble natural wind more than the reverse. A contemplative paper by Djamila et al. (2014) also suggests that people indoors expect a different situation. Our perceptions of thermal parameters are based on what we know or have experienced in the past. This means that people inside buildings do not necessarily anticipate natural wind.

2.4 Conventional Criteria

Above, the various sub-elements of the two domains, environmental and personal, have been addressed. Now that these elements are known, more criteria can be connected to them to determine what a PECS (Personal Environmental Control System) should fulfill. To do this chronologically, the areas of personal and environmental domains are juxtaposed: Control, Performance, and Robustness (figure 25). Control pertains to where the control strategies must comply, all lying within the personal domain, as they are tailored to the end-user. On the other hand, Robustness refers to the extent to which something can withstand variations, uncertainties, or disturbances without significant loss of quality, performance, or functionality (Attia et al., 2021). These aspects are determined by designers, implementers, etc. The degree of robustness determines how long and how effectively something actually remains in a particular context. In the middle, spanning both domains, is Performance, which is focused on both the control/end-users and the robustness of the implementer.

2.4.1 Control criteria

In the built environment, it has become nearly standard practice to limit user control. Therefore, the connection between the building and the user often relies on automated environmental control systems. These systems adjust to anticipate or react to changing environmental conditions and aim to fulfill occupants' comfort needs while minimizing energy consumption. Understanding the occupants' preferences for personal control is crucial in developing an energy-efficient automation strategy (Luna-Navarro et al., 2020). Automation can be chosen, where user control serves as a system override.

There are also several defacto standards for control strategies: light switches next to seated positions, click-up and down controls on cookers (up for on, down for off, increase clockwise, decrease counterclockwise) (Henry Dreyfuss Associates, 1981). Additionally, there are a few symbols universally accepted and recognized, at least in the Western world, as seen in figure 26(Bordass et al., 2007).

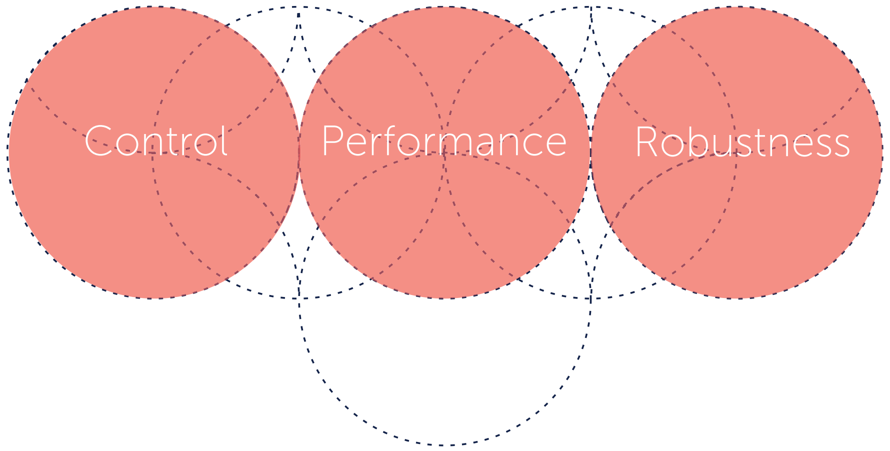


Figure 25: Graphical illustration of the domains of control performance and robustness across the fields of perception and environmental factors.

Elements that might also fall under default design standards for interfaces include the following (Bordass et al., 2007):

- *clarity of purpose*
- *intuitive switching*
- *labeling and annotation*
- *user-friendly interface*
- *responsiveness*
- *fine-tuning capability*

The question remains: what is the precise implementation of these factors regarding such a new system based on a personalized increase in air velocity? Because with the aforementioned factors alone, you do not have enough to determine control. What exactly is the clarity of purpose? What does intuitive switching entail in this context? What kind of response is desired? Additionally, how much control should one have?

Many of these factors are recognized in the field of occupant control, but their implementation depends on the future users. Essentially, the user background and expectations of the level of control are central. This determines the extent of occupant interaction in the end (Luna-Navarro et al., 2020).

2.4.2 Robustness criteria

The term integrated design primarily pertains to the front end of a new design, focusing on the effectiveness and costs associated with various actions. Essentially, decisions made early in the process have the most significant impact and ultimately prove to be the most efficient. The costs associated with these decisions are relatively smaller. Joining the process later, as an engineer, for example, results in less influence on the design/concept than those who came before. The likelihood of concessions that later prove disadvantageous is consequently high (Heiselberg, 2007).

Integrated design also involves how intelligently HVAC applications collaborate. A simple example is lighting. While everyone can provide their own lamp, central control of lighting is also possible. A combination is most desirable, providing individual control, but allowing central shutdown when, for instance, the building closes.

Deeply integrated elements, like windows in buildings, are challenging to change for users. In contrast, plugging and unplugging a device in a socket is simple and repeatedly usable. This phenomenon is common with temporarily appearing building elements and applications connected to the central climate system. For example, a temperature sensor may seem non-critical if it's simply plugged into a socket. However, removing the plug results in the absence of central temperature measurement, disrupting the system. A more robust design proposal would be to control the power supply centrally or create a housing that can only be opened with a key.

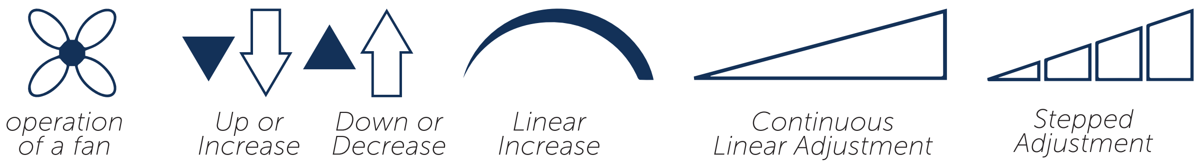


Figure 26: Conventional symbol standards (Bordass et al., 2007)

Maintenance-friendliness is also an incredibly important factor here because it involves not just individual spaces, but more collectively designed spaces where routine maintenance tasks such as cleaning, as well as replacing and checking components, are necessary. This also speaks to the product's lifespan (Bracke et al., 2017). This includes fans, which have a tendency to quickly accumulate dirt as a characteristic. Therefore, it is important to identify which type of fan is involved and whether a filter is required or not.

Flexibility and **Tolerances** are also crucial criteria in the design. Flexibility refers to the ability to adapt to changes or different situations without affecting performance or quality. Tolerance, on the other hand, refers to the extent to which a system, product, or process can tolerate deviations without leading to unacceptable consequences or errors. In other words, flexibility is about the ability to adapt, while tolerance is about the ability to handle variations without negative effects (RD8, 2022).

2.4.3 Performance criteria

This is essentially the section where control and robustness converge. From the previous section, we know, for example, the effective cooling areas along with the corresponding air velocities. It was found that the forehead and arms/hands are effective cooling areas under an air velocity ranging from 0 to 1.5 m/s. It's no coincidence that standards emphasize personal control because an unwanted airflow can be perceived as draught. Considering that everyone has different preferences, it's important for someone to have local control without inconveniencing others. Otherwise, you cause discomfort. Another form of discomfort is noise pollution.

Many fans generate noise, and while some may find it pleasant, others may find it bothersome. In a study by Huang et al. (2013), for instance, 50% of people reported not wanting to purchase a fan due to noise issues. Nowadays, many fans are significantly quieter. However, if there are 12 in one room, are they still all quiet? Sound is measured on a logarithmic scale, and a doubling of the number of devices results in a +3 dB increase. Moreover, excessive ambient noise is harmful and disruptive to the indoor environment. For a healthy indoor climate, around 35 dB of ambient noise is considered acceptable, with 40 dB being adequate and 30 dB considered very good (Platform Gezond Binnenklimaat, 2021). Additionally, noise pollution is one of the biggest issues for users of office buildings. According to Leesman (2023), only 35% of users are satisfied with the acoustics in the building. In summary, the less noise the application produces, the better.

One of the reasons for increasing air velocity is that it requires less energy than lowering the air temperature (Schiavon & Melikov, 2008). It is interesting to compare the wattage usage of each application to determine energy efficiency. Typical fans can vary in energy usage from 5 watts to 125 watts. For instance, the climate tables from Ahrend use only 54 watts for their ventilation provision (Rijksvastgoedbedrijf, 2022). While these numbers may seem relatively low per application, they starkly contrast with the energy required to cool buildings (both with air and water), and when combined, they can add up significantly. Therefore, it is essential for a device to require as little energy as possible.

The amount of square meters per person in an office building can vary significantly. In the Netherlands, minimum requirements are set per employee, with a minimum of 4 m2 for an employee. This includes the space where an employee can move, including chair space. Additionally, 1 m2 is allocated for a standard desk with a monitor, and in this scenario, we assume an extra 1 m2 for reading and writing space (NEN, 2010). This means per person:

- 4 m2 floor space
- 2 m2 desk space

Automatic presence sensors activate lighting and devices when people enter and turn them off when they leave. Adding buttons for manual control and using presence sensors to switch off things when they are no longer needed is often more economical than full automatic operation. Not everyone using the space may want to use the application. Therefore, it is advisable to have a manual **on/off button** (**override function**) (Bordass et al., 2007). Determining the override duration is difficult beforehand because the pattern of employee behavior is not documented in literature and is highly location-dependent. This also applies to the logical **positioning** of both the interface and the device. It is challenging to determine a logical position for a new device in advance. One person's desk may be filled with just a monitor, while another may require a lot of drawing space, and for yet another, it may be a flex workspace.

Everyone's thermal comfort is different, and individuals respond differently to their environment. No application exists that can perfectly predict and meet the needs of every user beforehand. Therefore, it is crucial to incorporate elements that empower users to control the location, amount, and direction of air themselves (Heiselberg, 2007).

Furthermore, as technical products become more advanced, there is a risk that the interface becomes overly complex and difficult for end-users to navigate. Simplicity is key when designing the interface for a technical product. Users should find it easy to exert influence over the system. Two important factors that determine a **user-friendly interface** are perceived playfulness and perceived usefulness (Lee et al., 2007).

The terms described above either address practical aspects or elements that require further development. Bordass et al. (2007) also discusses barriers. In one of the diagrams, it is explained that many control systems involve little input from clients and users, leading to a lack of discussion. Consequently, the interface becomes further removed from the user. They reason from their own perspective without considering the user's perspective.

2.5 Existing Airflow Applications

There is now a plethora of elements and criteria known to be important. Additionally, there are already numerous existing applications on the market that offer increased air velocity. Therefore, a comparison will be made with the existing knowledge to evaluate these products. Not all factors described above have been considered; rather, a selection that has already been reasonably elucidated in the literature.

2.5.1 Comparison methodology

The challenge in comparing existing applications that provide elevated airspeed are that many are designed with a consumer-centric focus, not as part of the built environment. Different factors come into play in such cases. Therefore, there is no single methodology that is 100% suitable for comparing various applications. This thesis utilizes a combination of two comparison methods: The Harris Profile and Weighted Objectives Method (Van Boeijen et al., 2014).

The Harris Profile graphically illustrates the strengths and weaknesses of a design concept. It is often used to evaluate existing designs and highlights areas of weakness (Van Boeijen et al., 2014). However, the issue with this methodology is that it is scaleless, which is crucial in this case. Quantitative factors such as sound (dB), energy usage (Watt), price (€), and qualitative factors such as user friendly interface are involved. These are units that cannot be directly compared but can be compared relative to each other for each product. Therefore, a combination is made with the Weighted Objectives method, which focuses more on determining the overall value of a concept (Van Boeijen et al., 2014).

Typically, the designer determines in advance what factors are important relative to each other and assigns weights to different components. Subsequently, the products are given specific ratings. In this thesis, each factor is weighted equally in this comparison. This is because the above-mentioned factors are seen as minimal requirements to visualize the comparison effectively.

As dimensionless numbers with units are compared here, all values are assigned a score indicating how the product performs relative to the item with which they are compared. The scaling for the various applications can range from -10, -5, +5 to +10. The "-" indicates a negative score, and the "+" indicates a positive score. Only factors such as sound, energy consumption, space usage vs workspace, and maximum price are scaled between 0 and -10.

The current products are compared based on the factors discussed above. They will not be tested on all factors because, for example, automatic presence sensors were not present for anyone, and an override function was not applicable, and positioning mainly refers to the work surface relative to the rest. Additionally, not all factors from the previous chapter on control are taken into account because terms such as clarity of purpose and intuitive switching still need to be defined in this context. However, the terms fine-tuning capability and user-friendly interface will be evaluated, as they are defined in this section.

The factors on which they are assessed are:

- Cooling effectiveness for the forehead
- Cooling effectiveness for the arms
- Ability to control without causing inconvenience to others
- Noise pollution
- Energy usage
- Space usage vs. Workspace needs
- Robustness
- Maintenance-friendliness
- Flexibility
- Tolerances
- Responsiveness
- Positioning
- Fine-tuning capability

Multiple devices are being considered that increase air velocity. These include:

1. Standing Fan
2. Big desk Fan
3. Bladeless ceiling fan
4. Ceiling Fan
5. Dyson.
6. Openable windows
7. Climate ceilings TNO
8. Climate tables from Ahrend
9. Partition PEC

There is a variety of different systems, ranging from products not specifically intended for this purpose, such as regular fans, to tested systems such as TNO's climate ceilings and Ahrend's climate tables.

On pages 50 and 53, graphical representations are provided to illustrate how the various applications from the test compare. In these representations, blue indicates negative aspects, while red indicates positive aspects. The comparison with the highest rating in red performs the best in the test. In the appendix, you can find detailed evaluations of each application.

The comparison will be further expanded, for example, by including factors like operable windows and personal ventilation that have been tested. The evaluation criteria may change as not all significant factors have been considered so far.

2.5.2 Results of the comparison

What stands out is that ceiling-bound solutions perform poorly, primarily because they fail to avoid inconveniencing others, their interface is not optimal, and they restrict users to specific locations. Additionally, standard fans do not perform as poorly as expected. They follow a similar trend to the desk Personal Environmental Control Systems (PECS). However, it should be noted that PECS primarily focuses on cooling the abdomen rather than the forehead and arms.

The comparison between TNO's climate ceiling and Dyson's fan is particularly interesting. While Dyson's fan is not specifically designed for this purpose, TNO's climate ceiling is. The Dyson fan performs relatively well in terms of performance, placing it higher than TNO's climate ceiling and

table fan (Ubuy Netherlands, n.d.)

standing fan (Ubuy Netherlands, n.d.)

bladeless ceiling fan (O'Donnell, 2024)

ceiling fan (Asahi Home Appliances, 2023)

dyson purifier (Dyson, 2024)

openable window (40 Mm Openable Window, n.d)

climate ceiling TNO (TNO, 2014.)

climate table Ahrend (DESKs | Ahrend, n.d.)

partition PECS (INIVE, 2023)

desk PECS (INIVE, 2023)

Figure 27: Table of compared devices

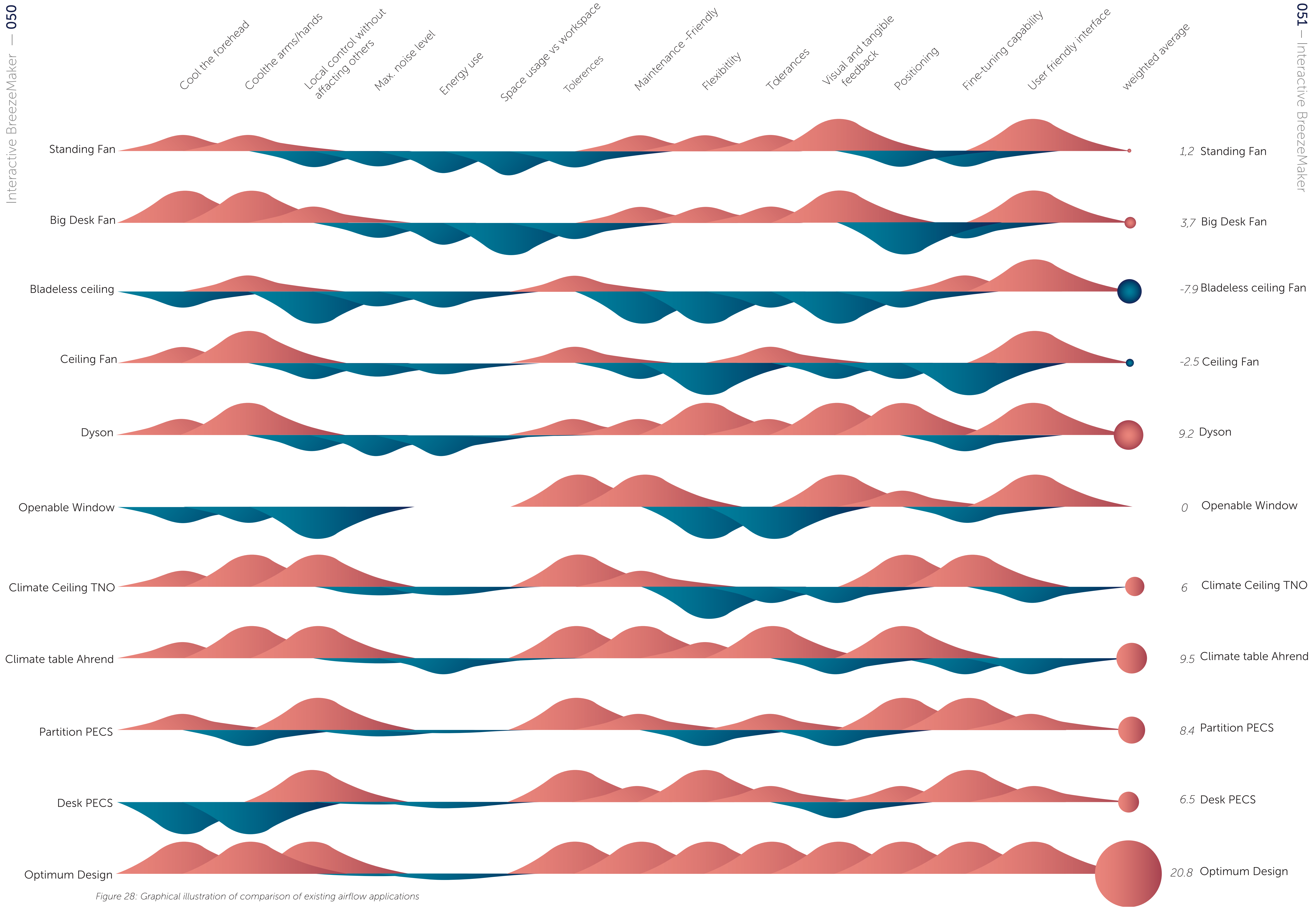


Figure 28: Graphical illustration of comparison of existing airflow applications

2.6 Dicussion & Conclusion

This section will discuss perceived control, thermal comfort, and airflow enhancement applications in open-plan office environments, aiming to integrate these findings into a unified discourse. The objective is to develop a comprehensive understanding of how personal control over environmental factors, particularly airflow, influences thermal comfort and the overall user experience. This discussion seeks to address the following three research questions:

- What is the effect of personal control on applications providing elevated airspeed?
- What is the effect of increased airflow on an individual's thermal comfort, considering parameters such as metabolic rate, clothing level, radiant temperature, air temperature, and humidity levels?
- What are the advantages and disadvantages of various applications that enhance airflow to promote thermal comfort?

The investigation into the impact of personal control over airspeed in open-plan offices underscores the critical role of perceived control. Personal control encompasses environmental, personal, and behavioral dimensions, and its efficacy is contingent on several factors, including clarity of purpose, intuitive switching, labeling, responsiveness, and fine-tuning capabilities. The conceptual model of perceived control highlights the necessity of understanding user experiences and expectations, which are pivotal for developing effective control systems.

The research reveals that individuals with an internal locus of control prefer customizable options, whereas those with an external locus of control lean towards automatic settings to mitigate choice stress. This dichotomy underscores the necessity for adaptive control systems that cater to diverse user preferences. The relationship between primary and secondary control also indicates varying perceptions of relinquished control, further emphasizing the importance of actual control, fine-tuning, and response speed in control systems.

Thermal comfort is significantly influenced by factors such as metabolic rate, clothing level, radiant temperature, air temperature, and humidity. The heat balance of the human body reveals that radiation accounts for substantial heat loss, and sweat plays a crucial role in thermoregulation. High humidity environments hinder sweat evaporation, necessitating increased air velocity to dissipate heat effectively. Research identifies optimal wind speed ranges (0.2 m/s to 1.5 m/s) for comfort, considering indoor settings with operative temperatures between 24 and 30 degrees Celsius and humidity levels between 40% and 60%, and activity levels ranging from sedentary to light office work (1.0 to 1.4 MET), with clothing insulation between 0.4 and 0.6 clo. Current standards set the limit at 0.8 m/s, above which the user should have full control. From the perspective of thermal comfort, it can be argued that fixed wind speeds above 0.8 m/s may still be comfortable for many individuals, but considering individual differences, it is unwise to enforce this universally. Therefore, it is important for everyone to have full control from 0 m/s.

The study also highlights the importance of individual differences in thermal comfort. Gender and the perception of wind source significantly influence preferred wind speeds. For instance, as temperatures rise, the difference in preferred wind speed between men and women becomes more pronounced. Furthermore, the source of wind, whether from a fan, air duct, or natural breeze, affects user comfort, with a preference generally leaning towards gentle, natural winds.

Variation in airflow emerges as a crucial theme in enhancing thermal comfort. While traditional approaches focus on maintaining environmental conditions within narrow boundaries, contemporary research suggests that variation is beneficial. Effects such as alliesthesia and thermal boredom underscore the need for dynamic environmental conditions. For example, horizontal wind along the body is more effective at heat dissipation than vertical wind, yet alternating between the two can create a more natural and comfortable environment.
Specific values for airflow parameters in temperate maritime climates suggest that a range of wind speeds and characteristics, including turbulence intensity and power spectrum, contribute to thermal comfort. Preferences lean towards winds with a power spectrum closer to β ≈1.8 and turbulence intensity between 40% and 60%. These findings emphasize the necessity for user-controlled airflow to accommodate individual comfort needs.

The comparative analysis of airflow enhancement applications reveals diverse design orientations and performance outcomes. By using criteria divided into three areas—performance, control, and robustness—and employing a hybrid methodology combining the Harris Profile and Weighted Objectives Method, a comprehensive evaluation of factors influencing these areas is achieved. The analysis shows that current ceiling-mounted solutions and standard fans often perform poorly compared to devices explicitly designed for personal environmental control. Notably, all devices tend to focus on specific criteria where they score highly, but none of the devices score high across all facets.

The research highlights the importance of responsiveness, defined as visual and tangible feedback, in control systems. However, a knowledge gap exists regarding what specific feedback is necessary for optimal user experience. Poor dialogue between clients/users and interface implementers further complicates the effective implementation of control systems.

Addressing the identified knowledge gaps requires further research involving stakeholders, including users, designers, implementers, and manufactures. Understanding the diverse experiences and expectations of users is crucial for developing effective personal environmental control systems. Additionally, incorporating insights from various stakeholders can enhance the usability and effectiveness of control systems, ultimately contributing to a more comfortable and productive work environment. In Figure 2001, the interplay between user experiences and expert insights regarding both environmental and personal domains is illustrated, demonstrating their interconnectedness with the three domains of control, performance, and robustness.

Future research should also focus on detailed implementation guidelines for airflow enhancement applications. While literature outlines important factors, it lacks comprehensive guidelines for practical application. This research could benefit from a multidisciplinary approach, integrating insights from environmental psychology, ergonomics, and engineering to develop holistic solutions.

The integration of personal control, thermal comfort, and airflow enhancement applications in open-plan offices highlights the complexity and interdependence of these factors. Effective control systems must cater to diverse user preferences, provide responsive and intuitive interfaces, and accommodate individual differences in thermal comfort. The emphasis on variation and dynamic environmental conditions aligns with contemporary understanding of human comfort, suggesting that adaptive control systems are essential for optimal user experience. Addressing the existing knowledge gaps through stakeholder engagement and multidisciplinary research will pave the way for advancements in personal environmental control systems, enhancing both theoretical understanding and practical application in the field of thermal comfort enhancement.

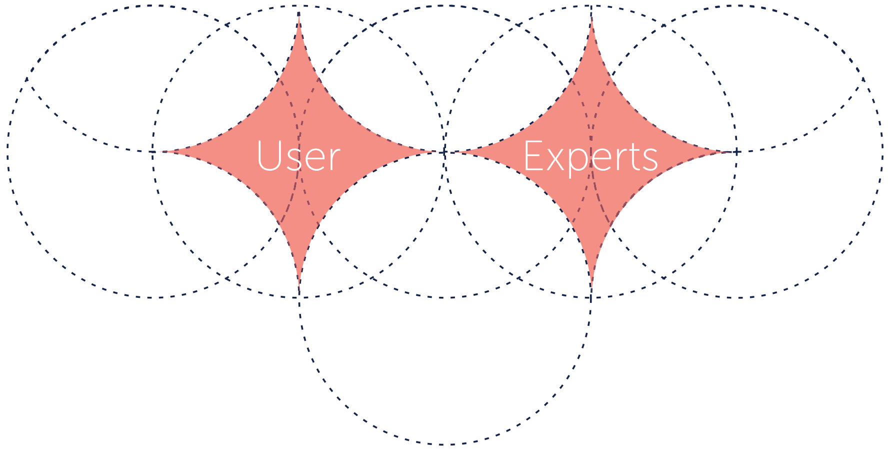


Figure 29: Graphical illustration showing the domains of user experience and expert insights across the fields of control performance and robustness

03

INTERVIEWS

3. Interviews

Previsouly from the literature part it became clear from the literature which parts of the body are effectively cooled and which design aspects are important, such as ease of use and intuitive switching. However, the aspects that end-users of office buildings consider crucial, and how they precisely define 'ease of use' and 'intuitive switching' for this new system, remain unknown in the literature.

Not only the requirements of the end-users but also other actors play a role in achieving an optimal system. It is therefore important to also understand the similarities and differences between these various actors in order to arrive at a set of design parameters specifically tailored for this system that meet the requirements and wishes of the users that experts consider feasible. This information will be obtained through interviews, based on three core elements: performance, perceived control, and robustness. The aim is to set up a definitive framework after these interviews in order to develop various design concepts related to the sub-question that needs to be answered:

How can we effectively integrate a breezemaker application integrated in open-plan offices?

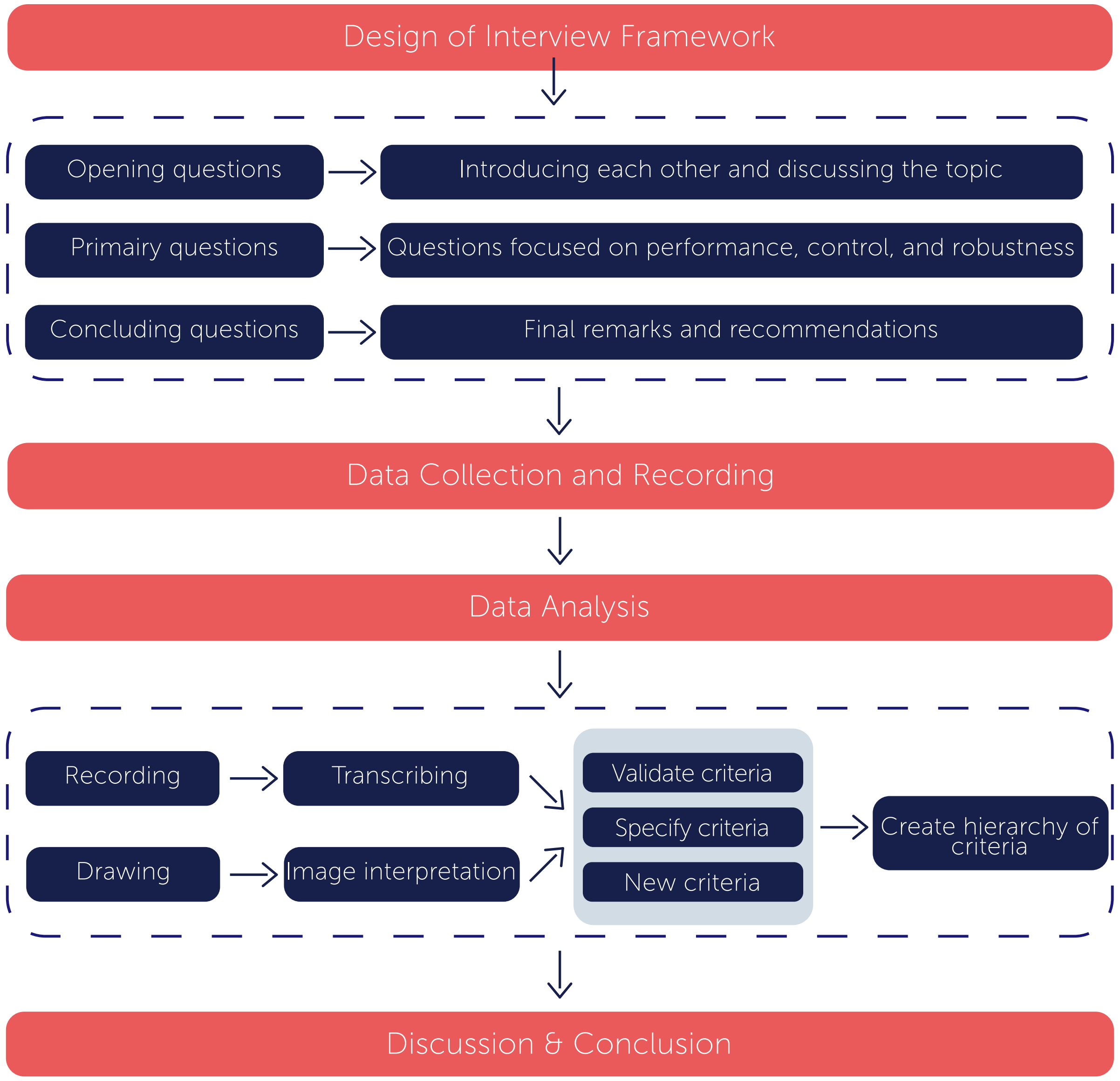


Figure 30: Approach and methodology of the research

3.1 Interview Setup and Methodology

To ultimately arrive at a valuable set of design parameters, the approach depicted in figure 26 is utilized, which will be explained in detail for each phase later.

3.1.1 Setup of interview questions

The interview takes place prior to the design process. This is to incorporate user experiences and expectations into the design from the outset. It also provides an opportunity to gain input from experts regarding current issues surrounding these products/situations. Qualitative information emerges from interviews. It is ultimately up to the designer to translate these qualitative requirements into something quantitative (Bruseberg & McDonagh, 2002). Therefore, a very structured interview is not used, but rather a semi-structured interview. This allows for more in-depth exploration and probing where necessary (Van Boeijen & Daalhuizen, 2010).

The interviews are focused on end-users. Many questions may not directly apply to the experts, but are addressed nonetheless because there is a significant possibility that experts, based on their expertise, can still contribute. The interviews are based on the therms that are discuseed in chapter 2. Each interview begins with a brief introduction of the user/expert followed by an additional introduction explaining the purpose and goal of the interview. The topic and objective are roughly outlined beforehand but are further clarified during the interview. Visual stimulation is used to explain the context visually and can be discussed in detail through this situation (Heijne & Van der Meer, 2019).

Visual stimulation consists of abstract/static situations and practical photos to highlight differences in office spaces. In the same environment used for visual stimulation, participants are given the opportunity to respond verbally and to draw in the situation. The performance questions primarily focus on the primary aspect of the new application: airflow. Where does the wind come from, what type of wind is it, and what is the quality of the wind? The second round of questions addresses how one would control that as a person in an environment where multiple people are present, and the interview concludes with questions about the physical design of the application, referred to as robustness. The areas of expertise of the various experts span multiple fields, which means they may not be able to answer all questions. However, due to their expertise, they are able to provide much deeper insights into certain questions than would typically be the case. Therefore, there will be a more in-depth exploration using the Who, What, Where, When, Why, and How, commonly referred to as the 5W1H questions. (Heijne & Van der Meer, 2019). The interviews are based on sessions lasting approximately an hour and can be seen in Appendix B.

3.1.2 Data collection

There are several criteria that the interviewees must meet. For end users, it is only required that they are employed (or have been employed) in an open-plan office or at least a shared office with 8+ people. Additionally, an attempt is made to maintain a gender ratio of 50:50 and to vary the age of the users.

For the experts, it is required that they meet the following criteria:

- Have at least one significant intersection with one of three domains.
- Have expertise in designing, implementing, and facilitating climate systems.

In this study, the snowball method was also employed, allowing participants to suggest other potential interviewees who are relevant to participate in the research (Fellows & Liu, 2015).

3.1.3 Data analysis

The interviews are recorded using an iPhone 12 with the Voice Memos app. The conversations are transcribed by Good Tape, where any mispronunciations/errors in transcription made by the author are later corrected.

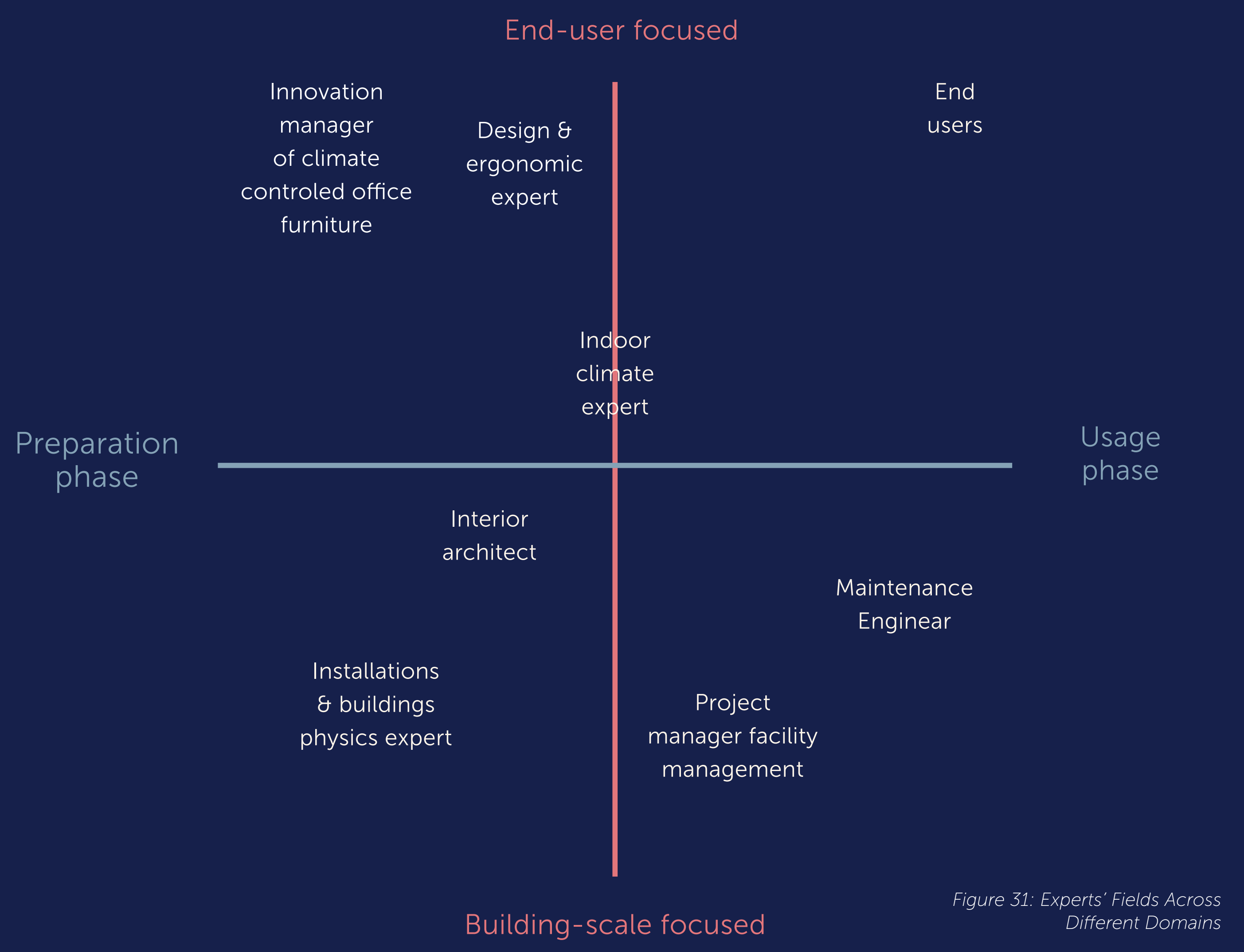


Figure 31: Experts' Fields Across Different Domains

Figure 32: User backgrounds

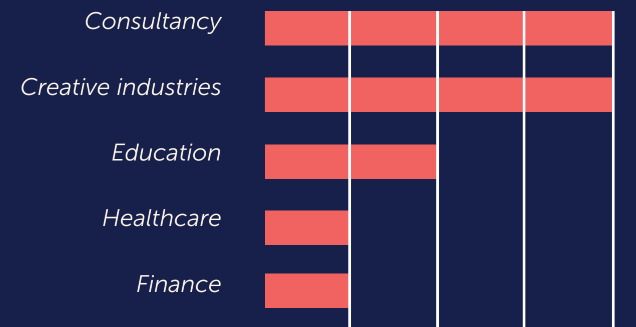
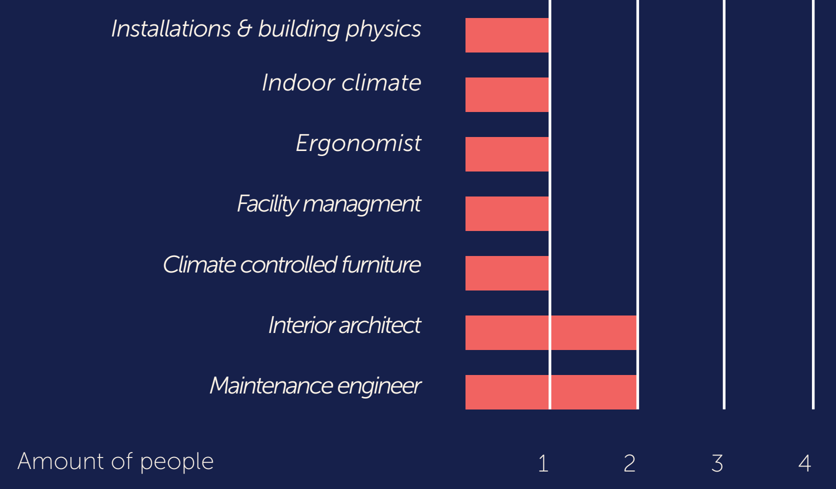


Figure 33: Experts fields



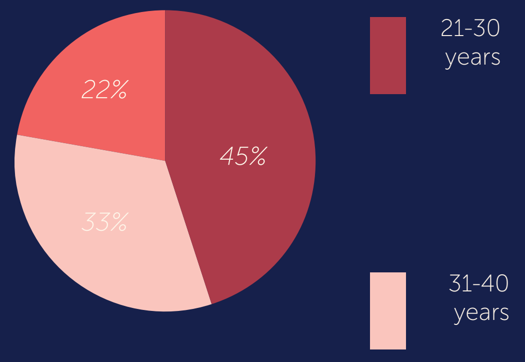


Figure 34: Age of users

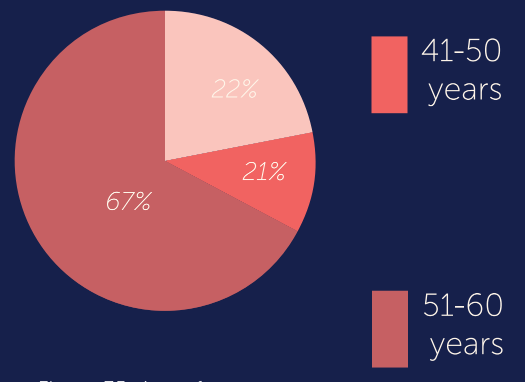


Figure 35: Age of experts

3.2 Results from Interviews

Between February 19, 2024, and March 8, 2024, a total of 21 interviews were conducted. 9 interviews were with experts, and 12 were with users of open-plan offices. All interviews, except for two, were conducted in person. The other two were held online via Microsoft Teams. The average age of the experts is higher than that of the users. The largest group of experts is aged 51 and above, whereas the users' age range is between 21 and 30 years (fiugre 34 and 35). Both 6 women and 6 men were interviewed among the users. Figure 32 indicates the sectors in which people from open-plan offices work, with the dominant areas being the consultancy and creative industries sectors. A total of 7 areas of expertise were consulted, with 2 of them also involving discussions with two experts each (fiugre 33). Figure 36 illustrates the various workspaces based on the standard dimensions of a desk (160 x 80 cm). This is important for tracing and understanding why certain responses are given by certain users as they often refer to their own situation. Most correspondents often work with two screens or 1 screen + a laptop (figure 36).

The findings of the interview are first approached in a general manner. Initially, they are scanned for important terms/factors based on frequency. Subsequently, an analysis is conducted to highlight significant factors. These factors may appear somewhat underrepresented in frequency but are still interesting to mention and can be found in Appendix C. Finally, a deeper dive is taken into the graphical elements encountered during the research, which may not necessarily have emerged from the text, and can be found in Appendix D.

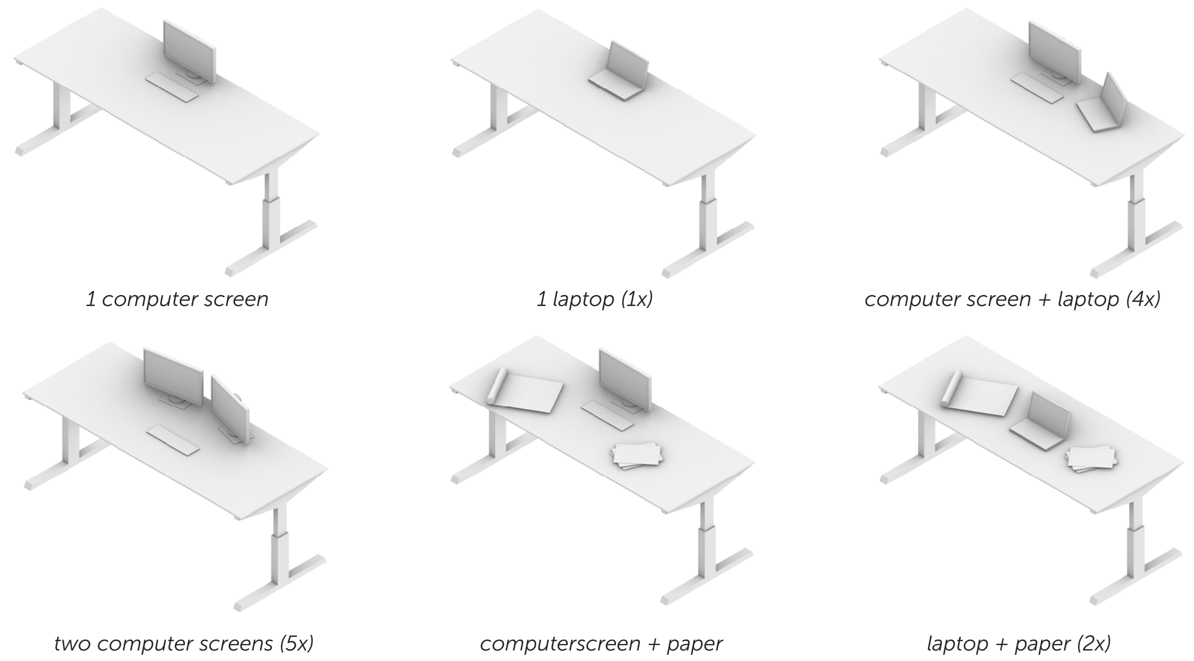


Figure 36: Table use of the different users

3.2.1 Word frequency analysis

In Figure 37 terms that occurred very frequently in the interviews are shown. The frequency of each term mentioned in each interview was counted, taking into account that the same words with different meanings were not added together. This is a general approach that nevertheless reveals certain relationships that are interesting to note. One could argue that factors frequently mentioned by users and/or experts signify their paramount importance to consider in the design process. The user group (12) is slightly larger than the experts (9), but it's not necessarily about the disparities between these groups; rather, it's about the variances within the expert group and what stands out overall.

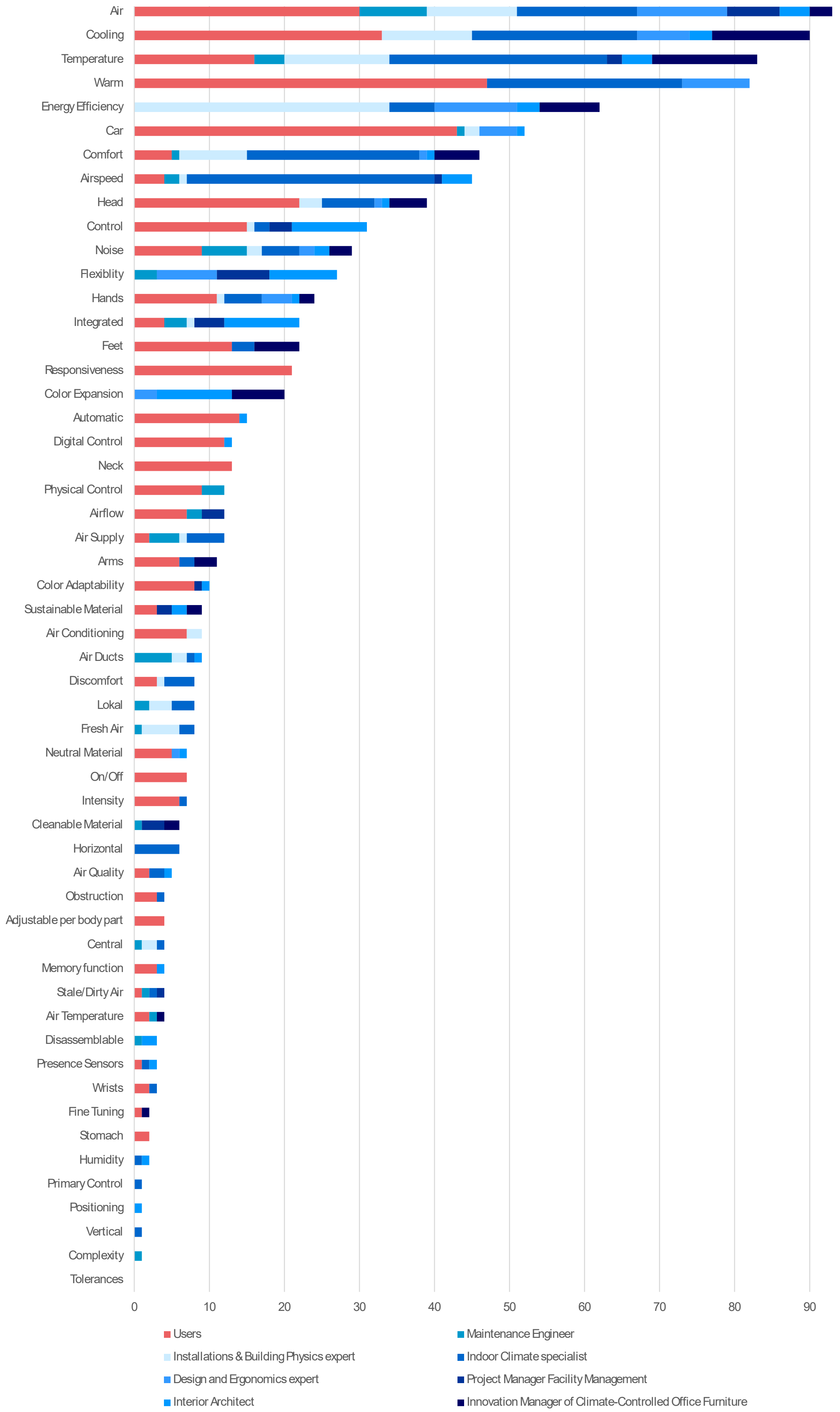


Figure 37: Frequency of mentioned terms

Several things stand out. The building physics expert discusses energy efficiency much more than comfort, for example, compared to the indoor climate specialist. The interview clearly indicates that all arguments are aimed at working as energy efficiently as possible rather than focusing on comfort. Additionally, comfort is a term heavily related to jargon; no user mentions the word comfort. They are more inclined to talk about feeling hot or cold. This observation is also evident in their communication. In the interviews, it is clear that their sensation of warmth/cold is immediately determined by an increased air velocity, over which they have control. This is emphasized by the interviewer. However, users simply feel hot or cold, or desire warmer or cooler conditions. In their communication, they do not realize that changes in activity, clothing, or air velocity can also influence comfort. They believe that only temperature determines their comfort level. The amount of energy expended is also not a concern for users. Although the word sustainable occasionally comes up, it is primarily focused on materials.

Sound is also a prevalent issue; people have many negative associations with things like fans or outside noise. Noise disturbance prevents people from using certain features and is often a dealbreaker. Both personal noise disturbance and consideration for others in the space are significant factors. People feel guilty if their actions cause inconvenience to others in the space. An interesting connection is made with the word "car." It is included because many people refer to a car situation, which surprisingly has a positive connotation. From their experience, there are many possibilities in a car environment, and there is no negative association with noise.

The interviews strongly indicate that people want certain parts of their bodies cooled, such as their head, arms, neck, and feet. Control over each body part is incredibly important to them. However, what users find equally important is responsiveness. Responsiveness is not mentioned at all by the experts but is highly valued by users. Its absence during the interviews, not highlighted by the interviewer, stands out. Another term that seemed more literature-focused, intensity, is frequently mentioned by users as well. They often struggle with the intensity of the airflow. Upon further questioning, they might feel there is too much wind directed at their head during a strong wind or storm outside.

3.2.2 Qualitative analysis

In the previous paragraph, we mainly discussed terms/themes that stand out due to their frequency of mention relative to each other. Not all important factors emerge simply because they are mentioned frequently. Some factors are more concealed but undoubtedly possess certain qualities that are important to consider as design factors. These factors are further detailed in appendix C.

Fine-tuning, particularly in an cars, is highly appreciated by the participants. The indoor climate expert also mentioned that fine-tuning at low air velocities is preferred by individuals. Conversely, manufacturers initially provided continuous control but later removed it due to excessive options. This preference for fine-tuning with recognizable points emerged during these interviews as well. Participants were asked their preference: 0-1, 0-10, or 0-100. The manufacturer offered 0-100, while all users indicated that this range was too extensive to remember, and 0-1 was too limited. They found 0-10 to be a comfortable means of control, despite it being dimensionless.

Presently, with the proliferation of smart building devices entering homes (e.g., lamps, sound systems, curtains), there seems to be a trend toward controlling things via mobile phones. However, during these interviews, almost everyone preferred a physical control option, preferably on the device, or alternatively in the third ergonomic zone. Some see the appeal or practicality of using an app, but users express reluctance to continuously adjust settings, especially for the same areas. Therefore, they consider it important for the system to remember basic/preferred settings that can be linked to their app or work pass. Additionally, an automation button can be helpful. Some users prefer the option to set the system to automatic, allowing them to fine-tune it themselves, rather than turning the device on completely and fine-tuning all settings from zero.

Integration is perceived as a crucial point from various perspectives. Integrated design contributes to higher robustness, which is desired by project managers and maintenance personnel. It also aligns with aesthetic considerations from interior architects and manufacturers. However, there's a significant tension here. For users, integration primarily means visually fitting in with the current or planned structure of the office environment. This differs from integration with other items.

A system may indeed be complex, as it typically undergoes a trial-and-error phase according to the manufacturer. However, it is crucial that the core of the product remains as simple as possible, and that its structure consists of very clear 'layers', making it easy to repair if something goes wrong. Maintenance personnel often identify this as a problem, as new systems often experience teething issues and are subsequently challenging to rectify in practice. Therefore, careful consideration must be given to what aspects of the design are made flexible and where the tolerances lie within the design. Flexibility pertains to the system's ability to adapt to changes, whereas tolerance relates to the system's acceptance of deviations or variations while still being able to function. Regarding flexibility, it is especially important to note that experts often highlight how office layouts change rapidly, hence a furniture-oriented solution often prevails over ceiling-bound solutions. Tolerances are particularly important within the system itself, as well as in its interaction with the environment. For instance, if something is attached to the ceiling, ensure that it is easy to relocate and adjust. Another example given by interior architects is that if something is loosely placed on the desk, it may also be an option to remove it if the table is used in a different manner

3.2.2 Sketch analysis

In Appendix D, the drawings/sketches made by individuals during the interview are presented. These drawings indicate where they would like elements to be placed within their workspace, where the airflow should go, and some have also attempted to draw a potential interface. It is noticeable that many participants draw objects beside the screens at the back of the desk. Ceiling-mounted items could also be considered, but no one draws anything in the traffic zones. These drawings also clearly demonstrate how individuals divide the body into three parts: top, middle, and bottom. Additionally, there is a strong reference to the car, which only has top and bottom, yet individuals still feel a need for a division between head and torso/arms. This reference is also evident in the symbols they use. No one uses a fan icon, but they do use icons commonly found in cars.

One aspect that wasn't extensively discussed verbally is how individuals want to fine-tune settings. Two interesting observations can be made. Generally, there is a preference for continuous control, often with numerical values. They also explained that this serves as a reference point for next time or for a different location. In how they alternate between buttons, symbols, and text, a clear hierarchy can be observed:

1. Button: fundamental element
2. Followed by symbol (sometimes combined with button)
3. Text: for explanation

Many individuals consider text important, but it serves more as a supportive element.

3.3 Discussion & Conclusion

This chapter endeavors to address the challenge of effectively integrating a breezemaker application within open-plan office environments. Through a comprehensive series of interviews with both end-users and experts, a spectrum of factors influencing the integration process has been identified. These factors encompass concerns ranging from energy efficiency to user comfort and control preferences. Additionally, the chapter underscores the significance of aspects such as sound management, fine-tuning options, and seamless integration with existing office infrastructures.

One noteworthy discovery is the disparity in perspectives between experts and end-users. While experts prioritize energy efficiency and technical specifications, end-users value comfort, control, and practical usability. For instance, while experts emphasize the significance of energy-efficient operations, end-users show little interest in that aspect. Another interesting finding is the significance of flexibility regarding application and workspace area. Flexibility is crucial as open-plan offices often undergo layout changes, even minor adjustments such as adding a single new row of tables. The literature suggests that the device should occupy minimal space relative to the workspace. This can be achieved by siting it outside the primary work area or by integrating it with specific elements or structures within the open-plan office.

Additionally, it is intriguing to observe the favorable experiences individuals have with automotive ventilation systems. Automotive ventilation encompasses more than just augmented airflow; it frequently entails the circulation of cooled air, which users find highly efficacious. Particularly noteworthy is the satisfaction individuals derive from airflow directed towards their feet, with minimal regard for accompanying noise levels, as activities vary. Nevertheless, noise remains a substantiated concern, closely intertwined with responsiveness. Responsiveness has also been substantiated as pivotal, particularly in the context of inconspicuous applications generating airflow, where users often perceive a lack of feedback.

Furthermore, the correlation between maintenance and the aesthetic appeal of the building is evident. Interior architects, who often occupy a prominent position in the design hierarchy, typically conceive spaces. No matter how superior a device may be, if it cannot be seamlessly integrated into the larger context in terms of color and texture, they will not incorporate it. Consequently, users resort to implementing disjointed systems, posing concerns for maintenance and building management due to the lack of oversight regarding electricity consumption. Maintenance professionals accentuate the intricacy they often encounter with new systems, emphasizing the importance of simplicity at the core, with expansions considered secondary. In the context of discussing fans, they particularly underscore the imperative to minimize maintenance demands for these devices.

Many respondents demonstrate a hierarchical preference in how they prefer to control systems, favoring buttons, symbols, and then letters. Significantly, numerous interviews underscore a physical interface as the primary mode of control, with additional options such as digital or centrally adjustable options considered secondary. An important consideration is the need for separate control of each body part. However, intensity control in this regard remains unspecified. Advice from an indoor climate expert suggests maintaining consistent intensity across the body, as a natural breeze uniformly affects the entire body. Intensity perception emerged as a notable theme during the interviews, appearing somewhat technical. While respondents were queried on intensity control preferences, many indicated that applications such as ventilators and automobiles often deliver airflow of excessive intensity. Hence, it is advisable to explore alternative methods to effectively regulate intensity perception.

It is important to note that there exists a degree of hierarchy among these factors. This hierarchy is apparent both in Figure 37 and Appendix C, where frequency partially determines this hierarchy. However, it is essential to emphasize that frequency does not necessarily dictate the hierarchy. While a digital interface is mentioned more frequently than a physical interface, a significant portion still prefers a physical interface over a digital one. Therefore, it is crucial to carefully consider this content. Moreover, it is not possible to fully ascertain the hierarchy without understanding its purpose. Merely relying on interview content with validation, interpretation, and frequency is not sufficient to establish a definitive hierarchy, as it needs to be examined in the context of existing literature. Additionally, criteria for its application and how distinctions are made need to be defined. This highlights a gap that requires addressing.

It might appear that the interviews are solely based on the subjectivity of the correspondents, but the interview questions are grounded in findings from the literature. The factors that emerged may have certain limitations, which further research could clarify. For instance, the group of experts was not extensive, yet it was certainly representative. Expanding the number of experts might have provided deeper insights, but for this phase, it sufficed. The group of users is gender-balanced but relatively young. Additionally, all interviewees are Dutch, which may offer insights for Western European countries but not necessarily for all countries in a temperate maritime climate.

An advantage is that almost all conversations were conducted in person, which puts people at ease, facilitates communication, and allows for a physical and visual understanding of things. This is also why the analysis based on frequency closely aligns with the interpreted descriptions of the terms in Appendix C. The quantity of terms used sometimes provides a good overview, but the devil is in the details; in the elements that are occasionally not explicitly mentioned and may not arise in conversation but are visually evident.

In conclusion, the integration of breeze-maker applications within open-plan offices presents a complex and multifaceted undertaking that demands careful consideration of various technical, ergonomic, and aesthetic factors. By embracing user-centric design principles and engaging with stakeholders from diverse backgrounds, designers can develop solutions that not only enhance comfort and productivity but also enrich the overall workplace experience.

04

FRAMEWORK

4. Framework

In this chapter, the criteria derived from the literature are combined with the interviews to form a framework. The purpose of the framework is to provide a validated overview that serves as a practical tool for designers to achieve a more validated and therefore effective design. This chapter clarifies which criteria are included and explains how the criteria relate to each other.

4.1 Must & Should Criteria

The interviews ultimately revealed a list of factors spread across the domains of control, performance, and robustness. The question is: which factors are vital for the success of a PECS and which factors are additional. To answer this, the factors are divided into "must" and "should" according to the MoSCoW method (Clegg & Barker, 1994) across the three domains of control, performance, and robustness. This is also known as MoSCoW prioritization. It is a way to show which functions or requirements of a project are the most important. By setting priorities, you can narrow the focus and set clear goals. The method uses four categories in which the different criteria can be classified: Must have, Should have, Could have, and Won't have.

"Must Have" refers to functions that are necessary and essential for the success of the device. Without these functions, the goal will not be achieved. Important questions to consider when placing factors in this category are: Which functions are necessary and irreplaceable? Or, if these functions are removed, would the project still achieve the same goal, or if not included, would the product still be a success?

"Should Have" functions can also be important but can be added later. Without these functions, the device can still operate at the desired level. However, if incorporated, it would elevate to a higher level. "Could Have" criteria are those where it is unknown if it is possible to add them. "Won't Have" focuses on factors that are not included. They essentially determine the constraints of the device. The last two categories are not included because the "Won't Have" is already defined at the beginning of the project, and "Could Have" is not included because the identification of the criteria is not at a level where it can be determined if those elements are feasible. This framework primarily draws attention to the factors we need to clearly understand as essential and those considered additional.

The definitions from the literature are clear about what is "must" and what is "should." But what does that mean in the context of this research? To decide which factors fall under "must" and which under "should," the following criteria are used:

- It meets the above criteria.
- There is an overlap between the literature and the interview outcomes.
- How important it is deemed by both users and experts, based on the highest criteria scoring according to frequency.

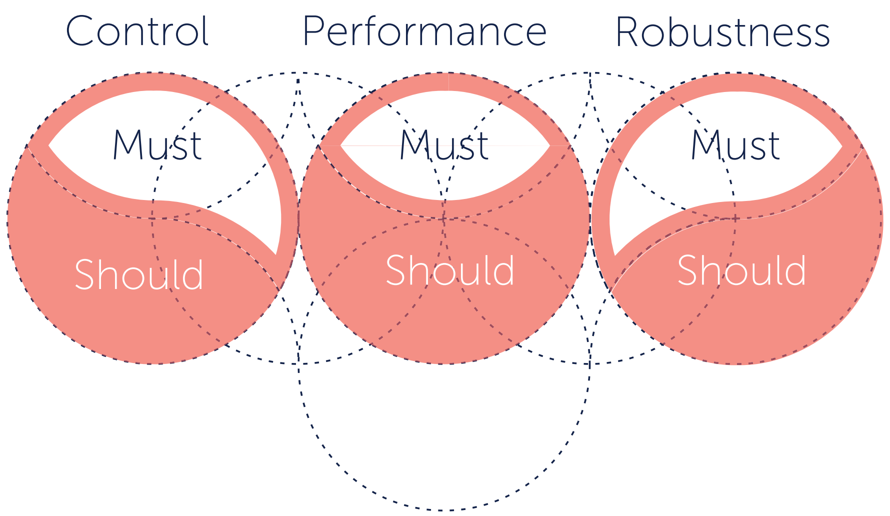


Figure 38: Graphic illustration of the distribution of the design factors control, performance & robustness in what must and what should

4.2 Design Drivers

After this brief introduction, you can read about the design drivers, followed by an explanation of how we arrived at this framework. Design drivers are essentially a list of requirements written in a narrative form. Earlier, we discussed the main factors, indicating which factors must be implemented and which should be. The design drivers also include sub-factors that present the complete picture. The reason for choosing design drivers instead of a simple list of requirements is that designing isn't just about ticking off lists; it's about the factors and their interconnections (Lesaffre, 2024). Through words, what is absolutely necessary, what is preferred, and what is optional are indicated. This way, the designer gets a sense of what truly matters and where there's still room for creativity, rather than strictly adhering to a rigid list. Take, for example, a knee brace. In a rigid list, terms like 'small' or 'compact' might be listed, but in reality, it's about the brace being 'invisible.'

In the following section, the various design drivers can be found in the areas of performance, control, and robustness, followed by a separate explanation of why certain elements must be included and others should be incorporated

4.2.1 Control

The device must provide **visual** & **tangible feedback** when it is on or requires maintenance, with the perceived wind as an additional response. Additionally, **each body part** must **be controllable separately** in terms of **direction** but with the **same intensity**. **Fine-tuning** must primarily focus on the 0 and 1.5 m/s range, utilizing a dimensionless scale with reference point between **0 and 10** or **the preferred** operative **temperature**. Furthermore, the communication revolves around warmer and colder rather than more or less wind. The entire control must be located in the **2nd or 3rd ergonomic zone.**

The application must include an **on/off button** and an **automatic function** based on the operating temperature at the workplace. It should also be adjustable through a **digital interface** with **memory capabilities** and/or **customizable settings**.

The primary mode of control must initially be **physical**, encouraging occupants **to interact with it**. The hierarchy of control must prioritize **physical buttons first**, **followed by symbols, and then letters** in a way that embodies a **playful design.** While a digital interface is currently a preference, it's not mandatory.

Pre-set functions should be combined with **presence sensors**. Optionally, the **central building management** should have a function to shut down all systems simultaneously.

Development of the control driver

All the aforementioned terms emerged in the literature. The hierarchy arises from the interviews. The key element identified in the interviews is the system's responsiveness, which manifests in visual and tangible feedback. Subsequently, people express that they prefer a gentle breeze, but specifically on parts of the body they find comfortable. Then, it primarily concerns the intensity, as it determines how the stimuli are perceived. The mechanical regulation lies within the performance domain, while the control domain governs how it is regulated. There are several ways to achieve this, but it is important to consider hand ergonomics to enable precise control over minor differences.

To cater to individuals with both internal and external locus of control, both a manual switch and an automatic button are required. Additionally, a physical interface must function effectively before transitioning to a digital interface. Memory capability functions can also be added later. Presence sensors and an option for central building management are choices that can be added later but are not primary for initial implementation.

To partially address the concepts of intuitive switching, playful design, and the management of labeling and annotation, the diagrams are referenced to clarify the hierarchical structure. Initially, communication occurs through physical buttons, followed by symbols, and then letters. It is important not to discuss the technicalities such as more or less wind; rather, focus on the effect: warmer or cooler.

4.2.2 Performance

The application **must not cause any disturbance**, so in a room, it must not produce more than **40 dB** of sound collectively and must not introduce any **distracting noises** to the environment. Additionally, it must not create a **bothersome airflow** for **other users** in the room. At the user's location, the device must be capable of delivering a speed ranging from **0 m/s to 1.5 m/s**, and preferably have a power spectrum close **β ≈1.8** and a turbulence intensity between **40% and 60%** where the **output surface area of the air** must be **as large as possible** to modulate the perceived intensity. When used for longer than an hour, there should be an automatic occurrence of **varying wind** speeds for 10 minutes, with the intensity corresponding to the given temperature. The position of the **device** must be in at least the **3rd ergonomic zone** or beyond.

There must be an **airflow directed at the head and arms** and should be targeted at the feet. Furthermore, the air quality from the application should be of the same quality as that of the base environment. If this is not the case, the application should be equipped with a **HEPA filter.** The filter can also prevent the fan from getting clogged with dust and makes maintenance easier. Finally, the device must be as **energy-efficient** as possible.

Development of the performance driver

In the realm of performance, it was confirmed through both literature and interviews that cooling the middle and top regions was preferred by users. Interestingly, while literature suggested that cooling the feet was ineffective, people find an airstream along their feet, similar to that experienced in a car, quite pleasant. Therefore, it is categorized as "should" because the effective operation of this feature has yet to be proven. Regarding the logical positioning of the device, various elements emerged. Literature strongly emphasized that it should not encroach upon the effective workspace. Interviews did not indicate any restriction on the use of the desk in this regard. Particularly, the third ergonomic zone appears to offer ample opportunity as it is passively utilized by the user for storage. Additionally, we understand from the literature the significance of 1.5 m/s, the type of wind concerning intensity and turbulence. It is evident that 1.5 m/s must be achieved, but the type of wind remains in question. The decision was made to address intensity immediately as it was prominently highlighted in the interviews. Therefore, it was chosen to maximize the output surface area considering energy efficiency, etc., which is now categorized as "must." An additional factor would be to examine the turbulence, variation in wind speed, and whether the power spectrum slope is at 1.8.

An important overarching factor that emerged clearly from both the literature and the frequency of interviews is that a personal environmental control system should not cause inconvenience to other users in the space. This means it should not produce disturbing noise or airflow that can be felt by others.

4.2.3 Robustness

The device must be **visually integrated** and initially based on an **basic office environment**, meaning it aligns with the current structure. Additionally, the standard size of **300 mm** is taken as the baseline measurement or **furniture size related**. **Maintenance** of the device must be **minimal,** with basic upkeep manageable by a non-expert, and its connection to other furniture must **not lead to dirt accumulation.**

The heart of the system must be as uncomplicated as possible, consisting of **clear layers** to facilitate easy troubleshooting. The object must not **hinder the flexibility** inherent in office spaces and should thus be **furniture-oriented** and it is preferred that it is **combined with an existing function** in an office environment. It must be **demountable** into main components. Furthermore, the installation process should be easy.

The device should generate as **little radiation as possible itself**, which means that a surface with **more texture is preferred over a completely smooth one**. Additionally, the material must be available in **various colors/textures**. **Tolerances** within the design should prioritize **user freedom** of movement, ensuring that fixed positions do not become obstructive.

Moreover, there's a strong preference for the **utilization of sustainable materials**. Additionally, the device should be a **detachable element** from the environment, leaving no damage behind.

Development of the robustness driver

When discussing robustness, the focus often shifts to integrated design. An important aspect to consider here is that it concerns integration for visual coherence and alignment with the current office structure. It is explicitly stated that integration with other functions is not a requirement due to complexity, but rather to maintain the freedom of layout. This viewpoint was mildly highlighted in the literature but predominantly emphasized by all experts. The freedom of layout is incredibly important. Another reason why integration is so crucial is maintenance. People want minimal to no maintenance, both because it is bothersome and because it incurs relatively high costs. Therefore, maintenance must be kept to a minimum, both in terms of the connection between the device and the environment and in terms of fan maintenance.

Practical-minded individuals particularly stress the complexity. In practice, many systems are so complex that when issues arise, which is common with new systems, something may break or new elements may become available later on. To ensure accessibility for maintenance purposes, each function should be situated in a separate layer that is demountable. Additionally, a relatively simple requirement is to offer the product in multiple colors and textures to provide interior architects with variation possibilities.

Tolerances are closely related to flexibility. Tolerances focus on precision and the acceptable boundaries of variation in specific characteristics of components, while flexibilities focus on adaptability and the ability to accommodate changes without compromising overall functionality or performance. Because flexibility is seen as one of the highest priorities, it was decided to make the tolerances of the physical design optional, as it is not something users specifically request, and it is advised to prioritize making it furniture-related. Therefore, adding tolerances is not the highest priority task.

Control

Precize adjustable per body part
Position the contol point in the 2nd or 3rd ergonomic zone
Design means for finetuning airspeed
Design means for automated function
Add memory capability function
Add presence sensors

Visual & tangible feedback
Communicate by using: 1. Buttons, 2. Symbols, 3. Letters/ Numbers
Design means for on/off function
Provide a physical analog control interface
Provide a digitial interface
integrate with central bulding managment system

Performance

Silent operation
Position the device in the 3rd ergonomic zone or beyond
Design means for targeting airflow to arms
Add HEPA filter (if necessary)
Design means for targeting airflow on feet
Design means for achieving an airpower spectrum slope β ≈1.8

Avoid draft felt by towards occupants
Selecting energy-efficient fan(s) to produce 1.5 m/s at user's location
Design means for targeting airflow to forehead
Balancing air speed and volume by maximizing surface area output
Provide automatic control of airspeed
Design means for achieving turbulence intensity between 40% - 60%

Robustness

Contextual and aesthetic integration
Keep each layer easy to separate
Base your design on a 300 mm grid or on furniture size
Provide devices in multiple colors and textures
Design the PEC as a detachable element from the building
Select material with low thermal emmissivity

Flexibiltiy towards the office floorplans
Design for easy maintenance to be done by non-experts
Design for ease of dissassembly
Design means to prevent dirt accumulation
Provide means for adjusting for personal selection of settings
Select sustainable materials

DESIGN CRITERIA
DESIGN REQUIREMENT
DESIGN CONSIDERATION (additional)

Figure 39: Desing criteria, requirements & considerations

4.3 Design Criteria, Requirements & Considerations

It is noticeable that many terms fall into the "must" group. This is because many requirements are basic elements that, in conjunction with the literature, have been deemed fundamental. All factors that must be incorporated are known, and a designer can work with them. The issue with the design drivers in which the "must" and "should" are incorporated is that the "must" group is too large to consider as criteria. Some functions are simply items that must be included, while other factors require actual design. Furthermore, there is also a sort of hierarchy within the "must" group itself. Looking at important factors, "no draft felt by other occupants" functions as a term that hovers above "airflow directed on arms and head," for example. Similarly, "visual & tangible feedback" ranks higher than a simple on/off button or automatic button.

Therefore, within the "must" group, a distinction is made between design criteria and design requirements. Design requirements are more detailed descriptions of what must be implemented or achieved in a design. They specify the functionalities, performance, and constraints of the design. Design criteria are standards or benchmarks used to evaluate whether the design meets the design requirements. Both are important, but criteria are used to assess the requirements. In Appendix E, the terms that appear most frequently are listed.

The design criteria are:

- *Noiseless*
- *No draft felt by other occupants*
- *Precise adjustment per body part*
- *Visual & tangible feedback*
- *Visual integration*
- *Avoid interfering with the office floor plan*

All these factors rank high in frequency and meet the above criteria. The reason why energy efficiency is not included as a criterion is that, although it is highly measurable, it is primarily mentioned by experts in the frequency list, not by users. It is important but not as a criterion. Additionally, introducing 1.5 m/s as a criterion would not add value to the design process. It is more of an action to be performed than a criterion by which to evaluate the design. The remaining factors are therefore the requirements. Many are formulated in a way that emphasizes their implementation. The difference between the requirements and the considerations was clear when distinguishing between what must be done and what should be done.

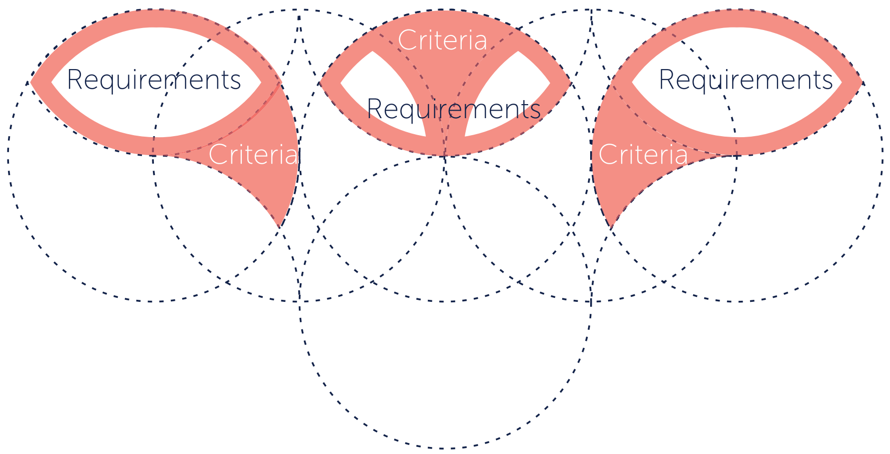


Figure 40: Graphic illustration of the distribution of the design factors that must be implemented in the requirements criteria

4.4 Ergonomic Manual & Workflow

The manual primarily provides guidance on how to initiate the design process. It mainly highlights the essential spatial dimensions of offices combined with human ergonomics. Because the physical interface is positioned at a distance of 90 cm from the user, certain fundamental dimensions such as font type, font size, and character orientation can already be established. This primarily focuses on what is visually perceived and how it is organised. Additionally, the areas suitable for air supply are also indicated. Many of the values are derived from this research, supplemented with basic values from human ergonomics (Henry Dreyfuss Associates, 1981). This manual offers guidance, but the designer must assess for themselves, for example, through physical models or testing, whether things actually function and if they are ergonomically comfortable to use. It is also possible to choose to create multiple variants and, for instance, present them to a focus group for feedback.

The question is: how do you begin the design process? A designer should first immerse themselves in the design drivers to understand how everything relates to each other. But designing begins by utilizing the evaluation system and ergonomic manual, two clear starting points for design. Where one starts is not defined, as that is up to the designer themselves. Some prefer to start with the bigger picture and work towards smaller details, while others begin with a small detail and then integrate everything.

The evaluation system is comprised of relatively simple elements. It's only the combination with each other that makes it complex. Because one design implementation may lead to hindrance in another. Therefore, it's important to have a systematic formulation in the design process that you can refer back to if you start to lose overview. The evaluation system is not explicitly defined as a workflow, as the workflow is something the designer determines themselves. There are various ways to deal with these evaluation factors.

Looking at the design requirements and considerations of the design, you can view these all as different sub-functions of the larger whole. For example, with the morphological chart method, one can develop these different functions (Van Boeijen et al., 2014). It depends on the scale of the sub-factors, but you can then assess the quality of the different designs using a Harris profile (Van Boeijen et al., 2014) with the design criteria (on the right in the diagram). Note: not all factors are suitable for this. Individual buttons are actually too small to be evaluated there. You can only evaluate them when they are part of a larger whole.

4.5 Validation of the Framework

The framework is based on literature combined with interviews. Ultimately, it still falls on the researcher to compile this. There is a chance that factors may not be interpreted correctly or something may be overlooked. Therefore, it has been decided to validate it with three experts. The experts in maintenance, interior, and manufacturers of climate tables.

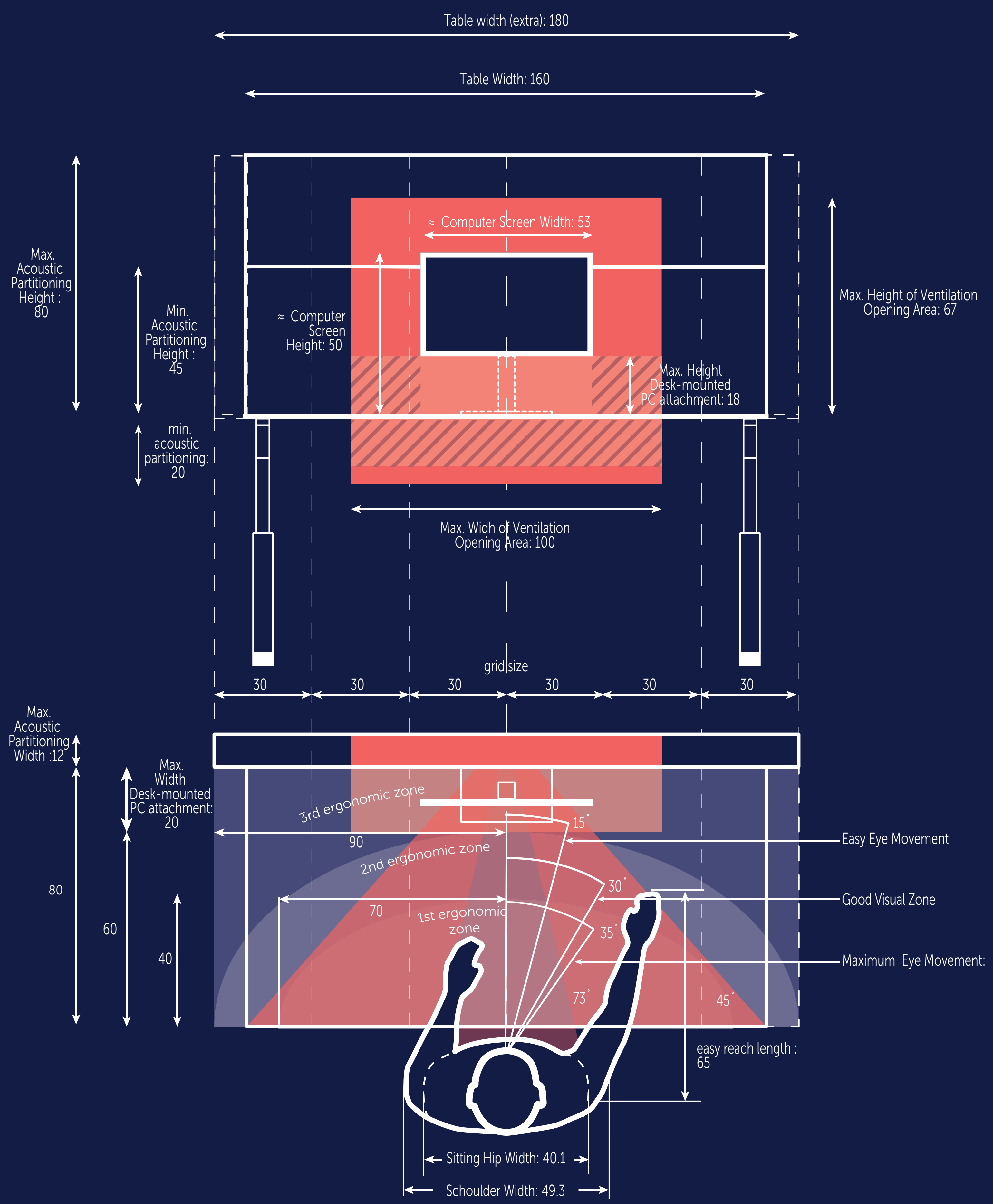
The maintenance team was positive about the framework. Especially about the fact that the system's basics remain easy while more complex elements have been added into the requirements and considerations. The most interesting discussion during this conversation was about primary control and in what form. They agreed that primary control lies with the end-user. However, within certain boundaries set from above. From experience, they know that many people leave systems on. Therefore, they advocated for fixed times when the system can be on. The difficulty is that office hours can vary widely, reducing the added value of this approach. The amount of hours saved is minimal. Therefore, they suggested a function where the system automatically turns off after 3 to 4 hours if no changes are detected. Their experience shows that many people only spend half a day in the same location, not a whole day.

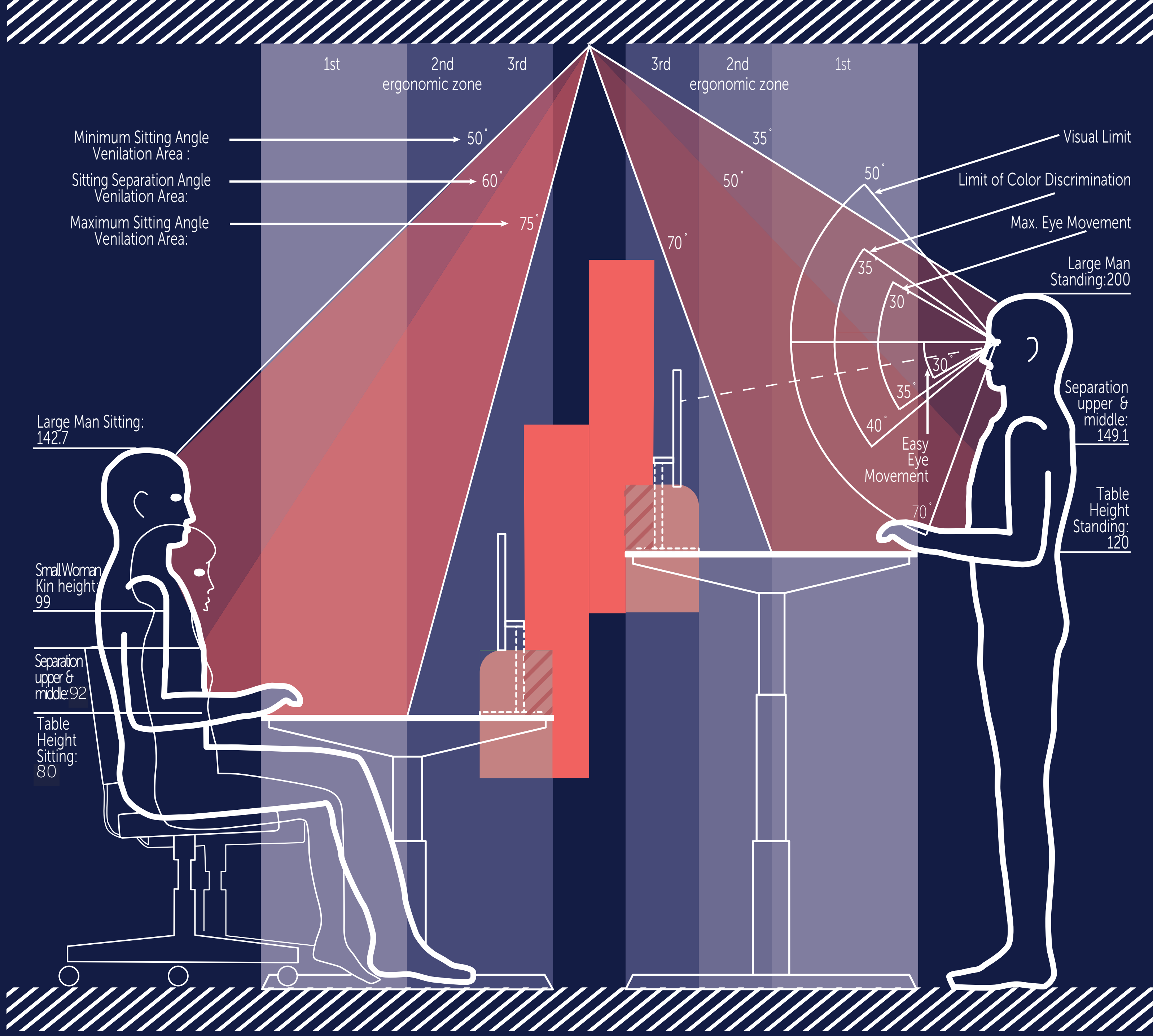
The expert dealing with climate tables mainly highlighted two elements. Both pertain to the hierarchy of different factors. The first was about design means to provide automatic varying wind. In the literature, thermal boredom is emphasized, which they also observe in practice. Continuous same wind is unpleasant, even though one can change it themselves. It should happen 'subconsciously' to prevent thermal boredom. Therefore, it is seen more as a requirement than a consideration. The second element concerned the memory capability function. They are concerned that as more functions and settings are added, people may not want to bother setting so many settings themselves every day. Therefore, the memory function is crucial. From the research, this remains important, but the importance of this function may be more applicable to climate tables in general than specifically to a device that only uses elevated airspeed for a summer situation.

As the final validator, the interior architect initially thought that certain elements might be self-evident to include, but later in the conversation, she realized their importance, especially in the climate sector. One requirement is that it is available in various structures and colors. This sounds very obvious and basic, but considering almost all interfaces that come from climate systems, these are all standard elements that are not customizable. There seems to be an advantage in everyone recognizing them, but the truth is that despite their similarities, there are always slight differences. For an interior architect, it's important to determine the look, especially the materials and color. So, are you going for metal or plastic buttons, what is their structure, and especially what colors are available. She also found the definition of ergonomic zones very strong but cautioned about the scale at which it applies. Namely, in an office of 40 people, there is often enough space. 10 cm at each desk may matter less there. While in an office of 1000 people, it's often tight. Where 10 cm with a standard desk width of 160 cm means a loss of surface area of 160 m2. That's immense. Therefore, it is advised to clearly emphasize effective space management in and around the desk.

Ergonomic Manual

Measurements for a BreezeMaker Device based on the minimum & maximum dimensions of the human body in centimeters





Visual Display

Letter Style :	Simple and Sans Serif (e.g., Futura, Helvetica, Venus or Gothic)
Location of Titles :	Above displays or controls (except when the control or display is above eye level
Character Orientation :	Prefer always vertical
Work Orientation :	Prefer always horizontal
Optimum Contrast :	10:1
Min. Contrast ratio:	3:1
Spacing Optimum between controlers:	1.9

Minimum Font Heigt 3.3 Routine Marking

Minimum Font Heigt 4.8 Critical Marking

Minimum Size of Indexes Low Illumination

Major Index : 7.1 x 1.1
Minor Index : 3.3 x .81

Intermediate : 5.1 x .91

Spacing : 2.3

Minimum Size of Indexes High Illumination

Major Index : 7.1 x .4
Minor Index : 2.8 x 0.4

Intermediate : 5.1 x .4

Spacing : 1.8

Organization

Panel Hierarchy :	1. Physical Button 2. Symbols 3. Letters
Panel Organization :	prioritiy controls first, related controls together, max 8 controls
Climate Communication:	warm(er) or cold(er), temperature up or down
On/Off:	Up/Down, Right/Left, Fwd/Back, Pull/Push, Clockwise/Counnter C
Increase/Decrease:	Up/Down, Right/Left, Fwd/Back, Clockwise/Counnter C
Raise/Lower:	Up/Down, Back/Fwd

4.6 Discussion & Conclusion

This chapter explores the question of how to develop effective methods for integrating a breezemaker application into open-plan offices. It emphasizes the necessity of establishing a coherent framework to address this challenge. Through a synthesis of literature and interviews, a comprehensive design brief comprising design drivers, an evaluation model, and an ergonomic manual has been formulated.

The study underscores the significance of not reducing factors to a mere checklist but meticulously distributing them across various domains. It begins with thoroughly delineating design drivers encompassing control, performance, and robustness. It became evident that distinguishing between what must and should be implemented was imperative. Waarbij must wordt gedfineerd als necessary and essential for the success of the device en shouldc an also be important but can be added later. The group of must-have features was notably extensive, posing challenges for designers and researchers to discern their true importance. Consequently, this group was further subdivided into criteria and requirements, with criteria serving as checkpoints for requirements.

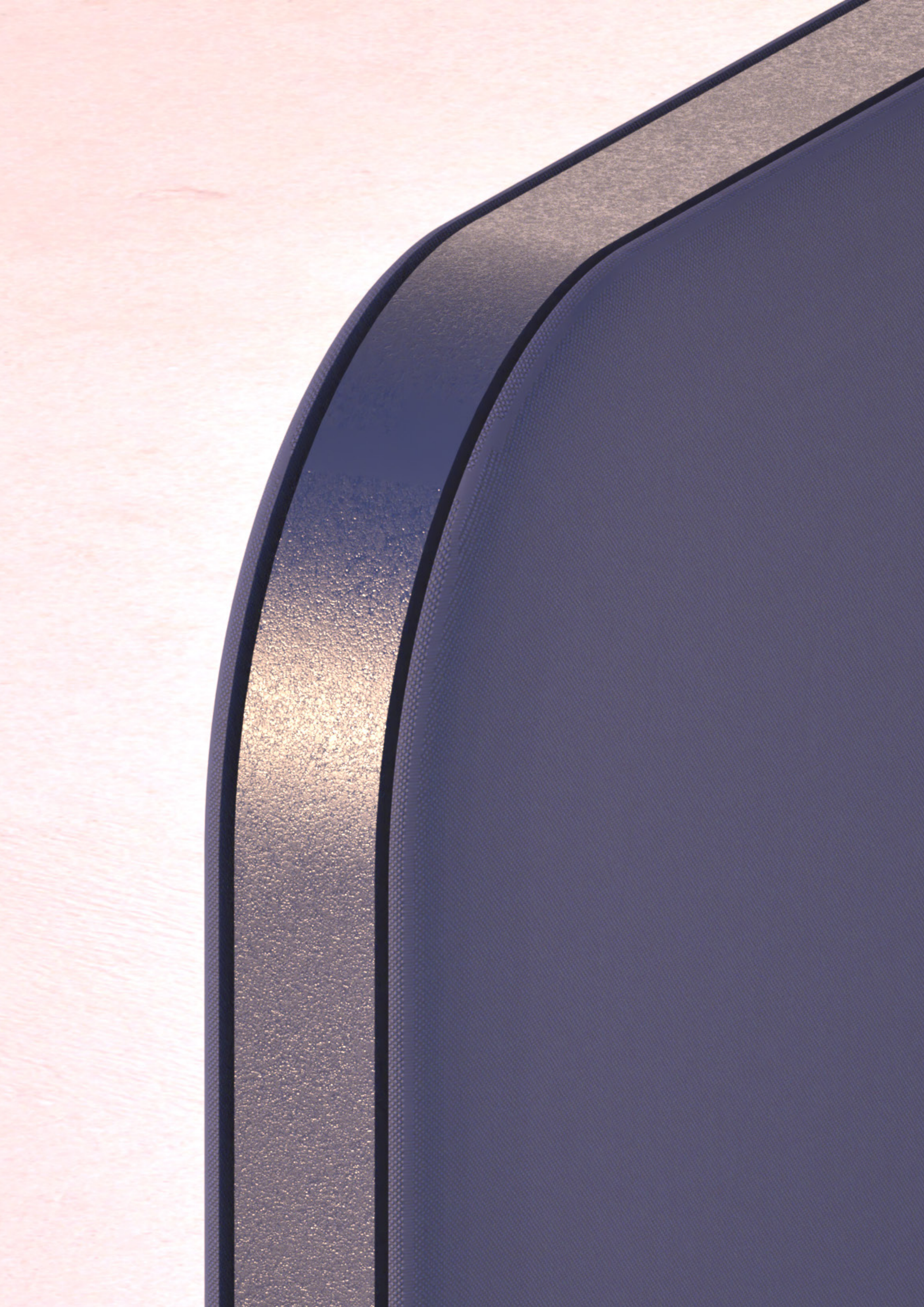
The design criteria take precedence at the apex of the pyramid, followed by requirements and considerations. Critical elements include ensuring minimal audible disturbance to other occupants, absence of noticeable drafts, precise adjustability for individual comfort, provision of visual and tangible operation feedback, and seamless visual integration into the existing office layout without impeding flexibility. While the first three criteria are corroborated by literature and refined, the latter three were derived from literature but required further specification, aligning with the overall narrative.

The resultant framework, albeit extensive and drawing from preceding chapters, has undergone validation on a smaller scale. The consensus among experts regarding the framework's viability is notable. A noteworthy revelation is the juxtaposition of energy efficiency with user convenience and ongoing debate over primary control. Although centralized building management ultimately dictates usage periods, users should perceive themselves as having primary control. Introducing time slots based on intervals emerged as a significant design enhancement. Additionally, as the number of functions increases, incorporating a memory capability function with personalized settings becomes pivotal to ensure user engagement. Interior architects particularly appreciated the emphasis on refining not just physical elements but also the physical interface, recognizing that both can be designed concurrently and that designers have influence in shaping them.

Two primary limitations of this specific framework merit attention. Firstly, the validation process involved only three experts and no end-users due to time constraints. However, the exhaustive exploration of literature and interviews offers a degree of validation, enhancing reliability. Secondly, while clarity of purpose and intuitive switching were explored, it remains uncertain if the framework adequately addresses these aspects. Further testing through design prototypes presented to focused groups is warranted to ascertain efficacy.

Future research avenues could involve practical implementation and iterative design processes, possibly involving user validation. This approach could yield deeper insights into intuitive switching and clarity of purpose, advancing the understanding of user interaction with such systems.

In addressing the subsidiary question, it becomes apparent that acknowledging a hierarchy in design factors is paramount. This research categorizes validated and specified factors across the domains of performance, control, and robustness into must-be-implemented and should-be-implemented groups. The magnitude of must-be-implemented features poses challenges in navigating further steps. Thus, a hierarchical approach is sought in delineating criteria and requirements, with criteria governing requirements.



05

Application of the Framework

5. Application of the Framework

In the previous chapter, there was a delve into establishing a solid framework that served as a guideline for the design of the project. This framework laid the groundwork for the criteria the design must meet and provided a structured approach to achieving the goal. In this chapter, there was further presentation of the actual design concepts that stemmed from the previously discussed framework.

The various subfunctions were approached using the morphological-chart method. Subsequently, a few subfunctions were evaluated using the Harris profile. From this exploration, three main concepts were then distilled that appeared most promising in fulfilling the specified requirements and objectives

5.1 Utilizing Design Requirements

In the framework, the evaluation system is included, containing the criteria, requirements, and considerations. These requirements and considerations are essentially subfunctions of the system. This marks the starting point of the design workflow. These subfunctions can each be designed independently and later integrated. This process utilizes the morphological chart method (Van Boeijen et al., 2014). The idea is to create multiple variants of subfunctions from which the designer can choose. The accompanying illustration shows this process in action. For the physical interface, fine-tuning options, on/off, and automatic preset functions, various sketches are made (figure 41). Next to it is a selection of what was ultimately sketched, giving an idea of the range. Ultimately, you choose the subfunctions that best fit and show the most potential. In this phase, the decision is primarily made by the designer. The following page shows how these concepts were further evaluated. When it comes to small subfunctions involving human ergonomics, it's important to test them at scale. Figures 43 through 44 show how various elements are made and tested at scale. Some test how they react to wind, others test the functionality when folding or twisting materials, and three physical prototypes were created in different sizes.

All three forms require different actions and differ in how they lie in the plane. For instance, the triangular hinges protrude from the plane, while the lower hinges are flush with the plane. The fabric outputs are elements that seal completely outside the plane. Each requires different actions considering hand ergonomics. This is also the phase where you seek the coherence of elements. However, this depends on the main shape onto which it is projected.

These smaller subfunctions are self-evaluated by the designer. A combination of these functions or scales, as shown in figure x, can be assessed by dedicated focus groups. There is also another technique for the designer to achieve a more systematic design approach without consulting others, which is more objective.

This brings us back to the main form. This is a larger subfunction suitable for evaluation using the Harris profile (Van Boeijen et al., 2014), providing a more systematic evaluation method. This can be completed by oneself or another person. In this case, the designer did it themselves. The Harris profile is rated as -10, -5, +5, or +10, with no option for a middle ground to ensure clear decisions. I evaluated all the subfunctions related to cooling arms, head, and feet based on the six design criteria. Feet were included despite being a soft criterion:

- Noiseless
- No drafts
- Precisely adjustable per body part
- Visual and tactile feedback
- Visually integrated
- Avoid interfering with the office floor plan

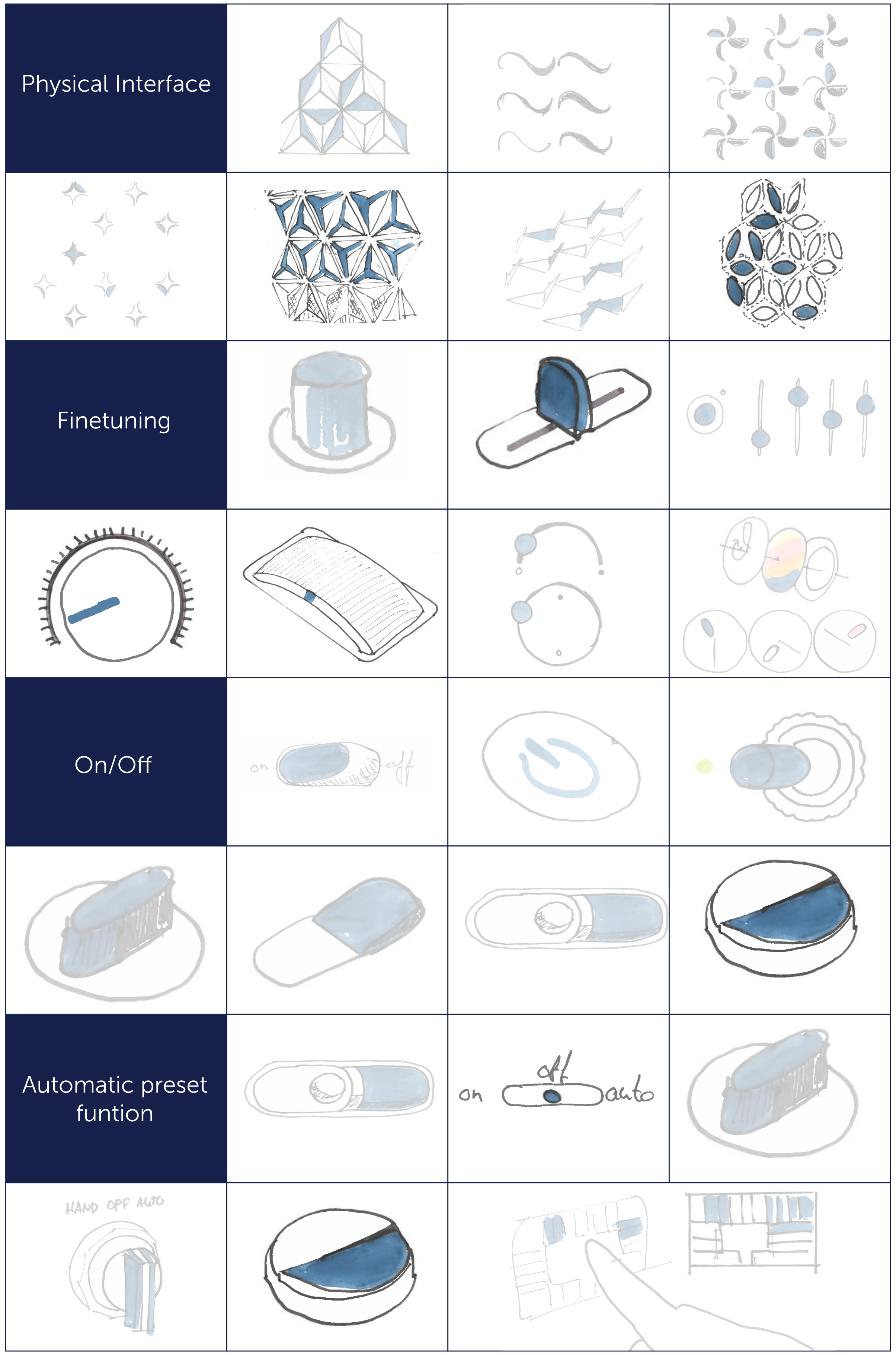


Figure 41: Morphological Chart of Subfunctions of the Interface

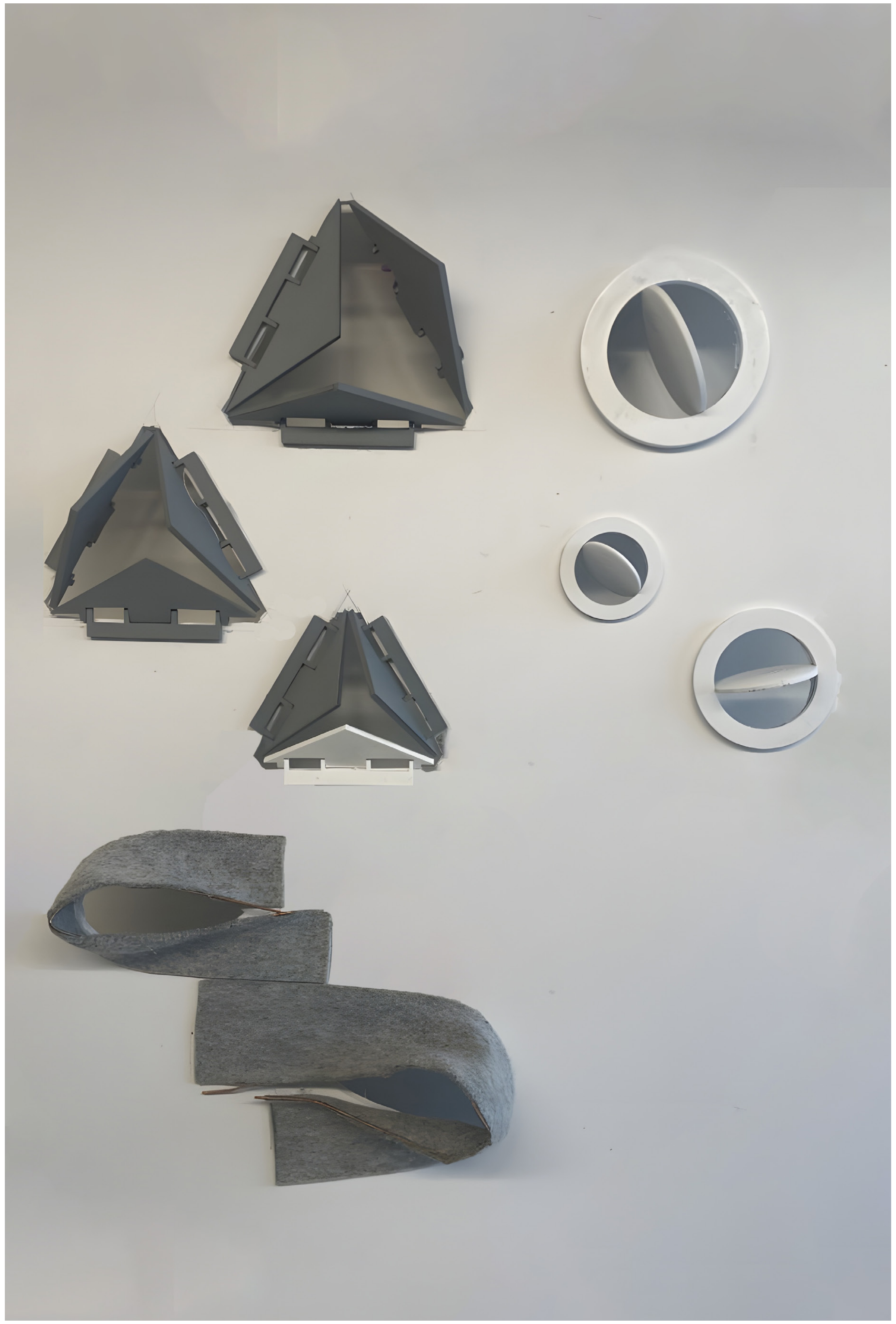


Figure 42: Ergonomic test setup of ventilation opening with hinge point in, on, and outside the plane in various sizes

These functions are better suited for the final design stage, as well as for the main form. Specifically, the farther away from the occupant, the greater the chance it is noiseless, and the closer to the occupant, the less likely they are to feel a draft from another source. In the 2nd and even the 3rd ergonomic zones, it is best to adjust the airflow. When a product is in front of you, you receive more direct and tangible feedback than when it goes through a separate interface first, no matter how precise that may be. Visual integration depends on how it aligns with the office structure. Limitless office space flexibility ensures that if there is a change in layout, the product can easily adapt.

To determine the main form, the design requirements for airflow design in the head, arms, and feet areas were used as a starting point. The process begins again with the morphological chart method to generate various ideas for these three subfunctions, which are then evaluated. Pages 84 to 87 show the morphological chart in combination with the Harris profile.

Figure 43: Testing some folding techniques for ergonomics and the route of the air

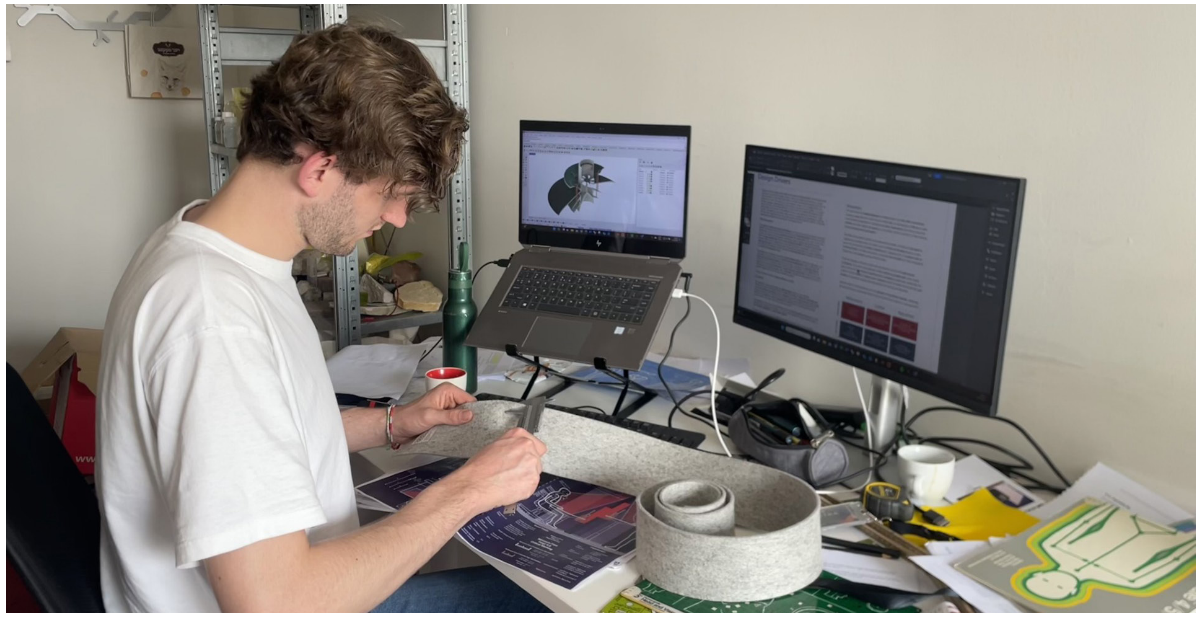
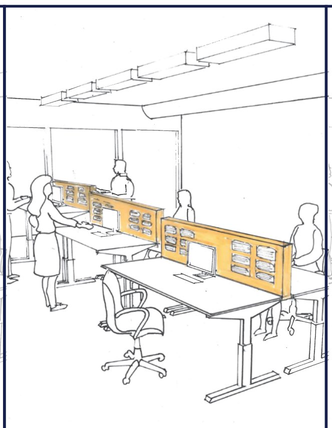
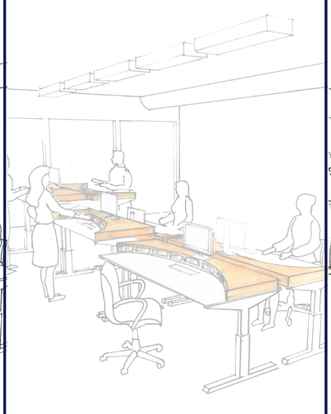


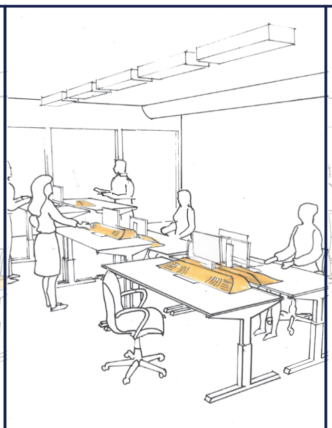
Figure 44:Taking measurements of felt to determine the ergonomic possibilities

Airflow on Arms


under the desk (5)


partition(35)


full 3rd erg. zone (15)


flow under pc screen (35)

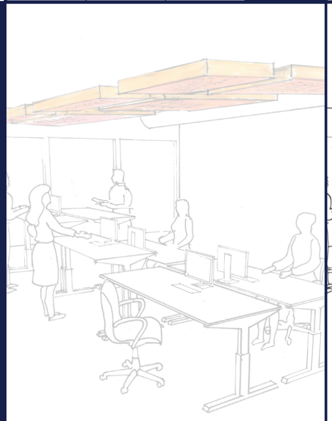

box under pc screen (15)

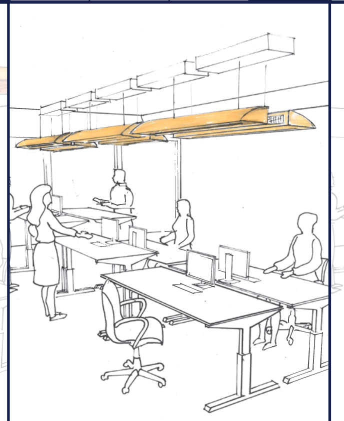

lamp idea (15)

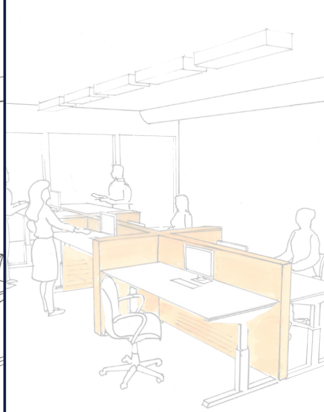

side elements (20)

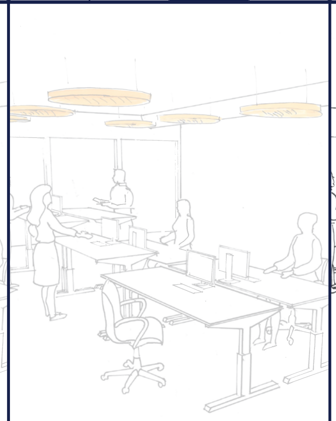
	under the desk (5)				partition(35)				full 3rd erg. zone (15)				flow under pc screen (35)				box under pc screen (15)				lamp idea (15)				side elements (20)			
	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10
Noiseless	■					■				■				■				■						■		■		
No Draft felt by Others				■				■			■					■				■		■					■	
Precize Adjustable per Body Part	■						■					■				■				■		■						■
Visual & Tangible Feedback		■					■				■					■				■			■					■
Visually Integrated				■				■		■					■			■						■		■		
Limitless office space Flexibllity				■				■			■				■				■					■			■	

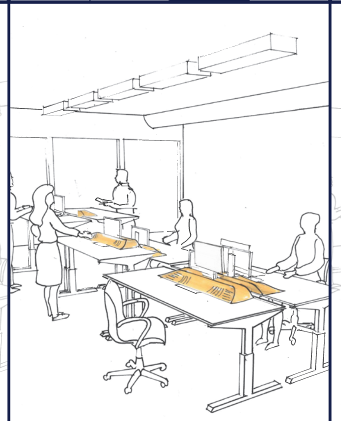
Airflow on Head


suspended ceiling idea (20)

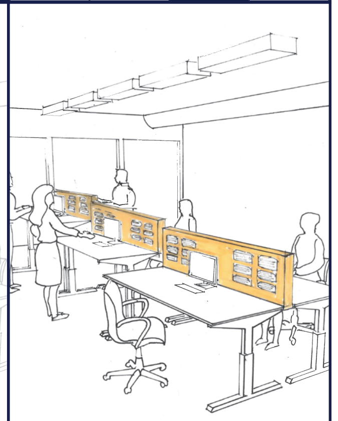

lamp idea (25)


180 degree partition (10)


round ceiling idea (20)

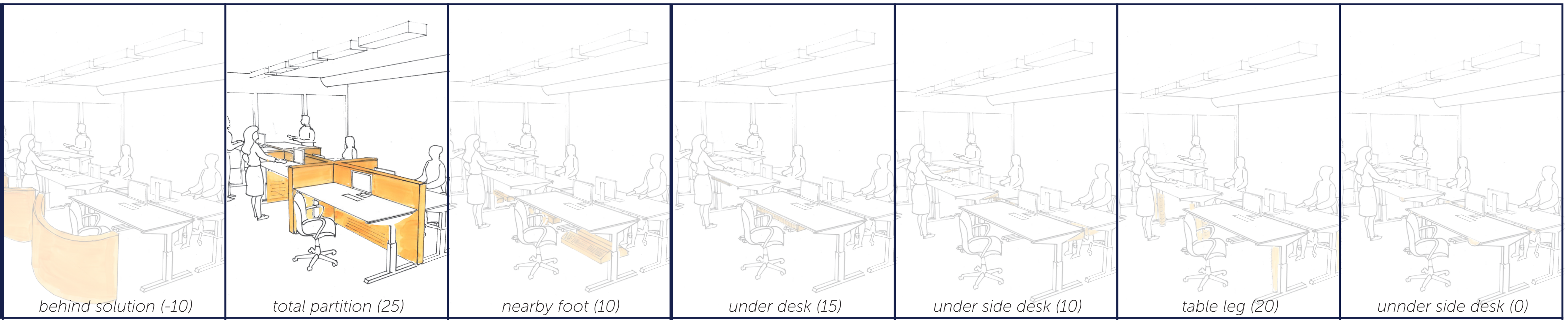

flow under pc screen (30)


side elements (15)


partition(35)

	suspended ceiling idea (20)				lamp idea (25)				180 degree partition (10)				round ceiling idea (20)				flow under pc screen (30)				side elements (15)				partition(35)			
	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10
Noiseless			■				■			■					■			■				■				■		
No Draft felt by Others			■				■					■			■					■			■					■
Precize Adjustable per Body Part			■					■				■			■				■				■				■	
Visual & Tangible Feedback		■				■				■				■						■				■			■	
Visually Integrated			■				■				■				■				■			■						■
Limitless office space Flexibllity			■				■			■					■				■				■					■

Figure 45: Morphological Chart with Design Considerations evaluated with Harris Profile



Airflow on Feet	behind solution (-10)				total partition (25)				nearby foot (10)				under desk (15)				under side desk (10)				table leg (20)				unnder side desk (0)			
	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10	-10	-5	+5	+10
Noiseless		■				■					■		■						■			■				■		
No Draft felt by Others				■				■				■				■				■				■				■
Precize Adjustable per Body Part		■						■				■	■					■					■			■		
Visual & Tangible Feedback	■							■		■					■			■				■				■		
Visually Integrated		■					■			■						■		■					■			■		
Limitless office space Flexibllity			■			■				■						■				■				■				■

Figure 45: Morphological Chart with Design Considerations evaluated with Harris Profile

By evaluating the morphological chart method with the Harris profile, I have arrived at three main concepts. From the matrix, a total of six items were selected and combined into three primary forms: a dismounted element, a desk partition element, and a ceiling-mounted element. For the design process, we decided to proceed with three concepts, hence we continued with these three. There was an overlap between the designs of the head and arms. Below, you can see three main forms that have been further developed and combined with other requirements. Each design concept will be explained separately. Each concept also has an interface. All interfaces are different in their entirety, but there is an overlap between these interfaces. First, the following pages will explain what each interface has in common. Then, each design concept will be explained individually along with the additional interface.

By evaluating the morphological chart method with the Harris profile, I have arrived at three main concepts. Below, the three developed variants can be seen at a more advanced stage. Each design concept will be explained separately on the following pages. Each concept also has an interface. All interfaces are different in their entirety, but there is an overlap between these interfaces. First, the following pages will explain what each interface has in common. Then, each design concept will be explained individually along with the additional interface.

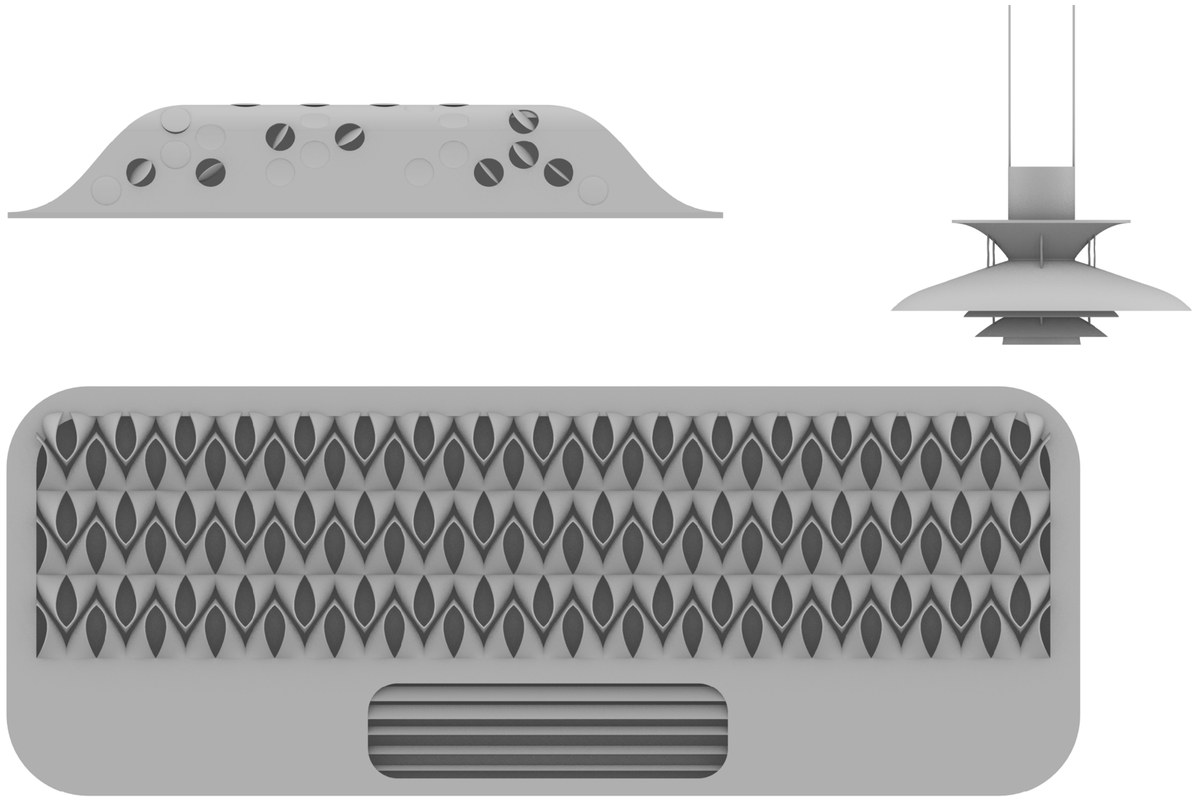


Figure 46: The Three Design Concepts: Desk-mounted (top), Ceiling-mounted (middle), and Desk Partition (bottom)

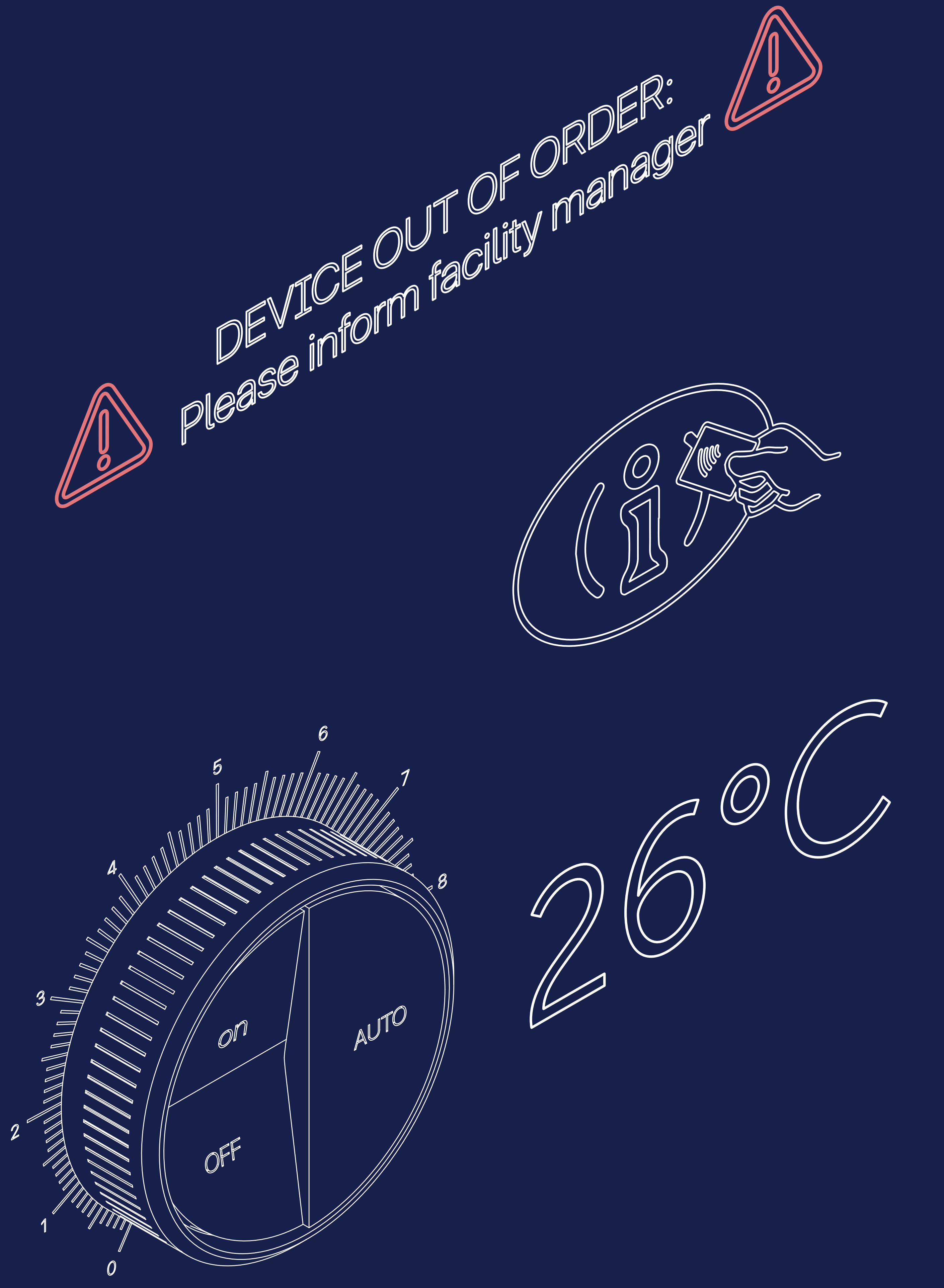


Figure 47: Interface lay-out

5.2 Design Concepts

Below, the interface applicable to all three concepts will be discussed first. Subsequently, the specific concepts will be addressed, where the additional interface needed for each will be discussed.

5.2.1 Interface

To operate the application, each interface must contain at least three items. This is fundamental. The number of buttons should be minimized while maintaining clarity, emphasizing a minimalist design that visually differentiates the various elements. This approach is inspired by Braun Design (Product Design Company, End-to-End Product Development - Design 1st, 2023). The minimalist design aims to eliminate unnecessary elements, focusing on what is essential for the user. This philosophy has been adopted by many design brands, such as Apple.

Among the various sub-functions, a few items are highlighted in pink. The intensity button is combined with an on/off button for users with a strong internal locus of control, and an auto button for those with a strong external locus of control. The automatic button adjusts based on the operative temperature. The display allows for very fine adjustments between 0 and 10, effectively providing a continuous scale with additional steps between 0 and 1. This enables users to remember specific settings and make precise adjustments. Alternatively, the display can show the operative temperature. For example, if the operative temperature is 28 degrees, according to Zhai et al. (2017), the preferred airspeed is 1 m/s (figure 47) , which can cool you by 3 degrees, making you feel 3 degrees cooler locally (figure 48). The automatic button adjusts the airspeed based on the operative temperature, which may not always match the user’s preference. However, users with a strong external locus of control might find this automatic control satisfactory and leave it unchanged, similar to adjustments in a car.

Each device includes an initially invisible indicator. When the device malfunctions, you receive visual and tangible feedback. If it is broken, a message will appear: DEVICE OUT OF ORDER: Please inform the facility manager. The entire interface will switch to a red color, signaling the need for action (Henry Dreyfuss Associates, 1981).

Finally, there is an option to hold your employee card, phone, or another card against the device. Using your employee card, you can access preferred settings automatically. You will be redirected to a separate site of your organization, where we, the designers, provide a digital interface and can answer more detailed questions about how to optimize comfort in buildings beyond this device. This feature is especially useful for flexible spaces where settings cannot be saved. Upon arrival, you simply place your card on the device, and your preferred climate settings are automatically applied. The device remembers your preferred speed in combination with the operative temperature, enhancing the reliability of the automatic button.

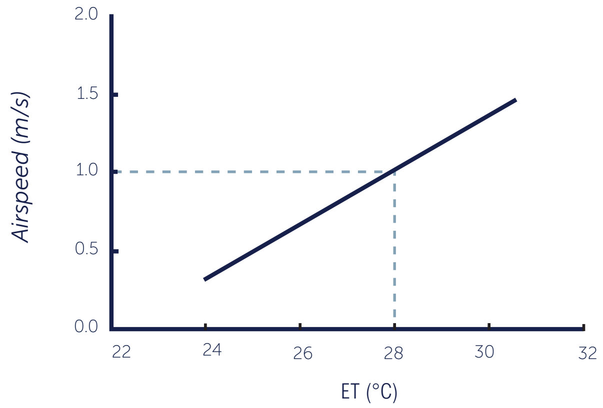


Figure 48: The prefered airspeed by 28 °C (Zhai et al., 2017)

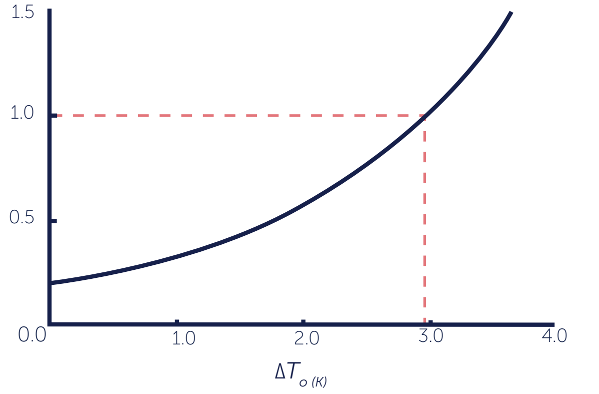


Figure 49: Elevated airspeed in relation to cooling (NEN-EN 16798-1, 2019)

5.2.2 Deskmounted Element

Here, the main element is positioned in the 3rd ergonomic zone below a monitor. This ensures that the ergonomics of the monitor are not hindered by lowering it. The application flow actually goes towards the sides and can be executed in multiple materials. The materials frequently come into contact with the user. The output is currently done in the form of circles. However, it can actually be any shape as long as the surface areas of that shape meet the energy consumption maximum. Both the arms and the head can be individually cooled because these elements can be rotated 360 degrees. The air is drawn from the rear and there is a possibility of a filter. The basic interface provides visual and tangible feedback. The solution can fit on both a 1600 and 1800 mm table and is a furniture-mounted solution that is completely demountable.

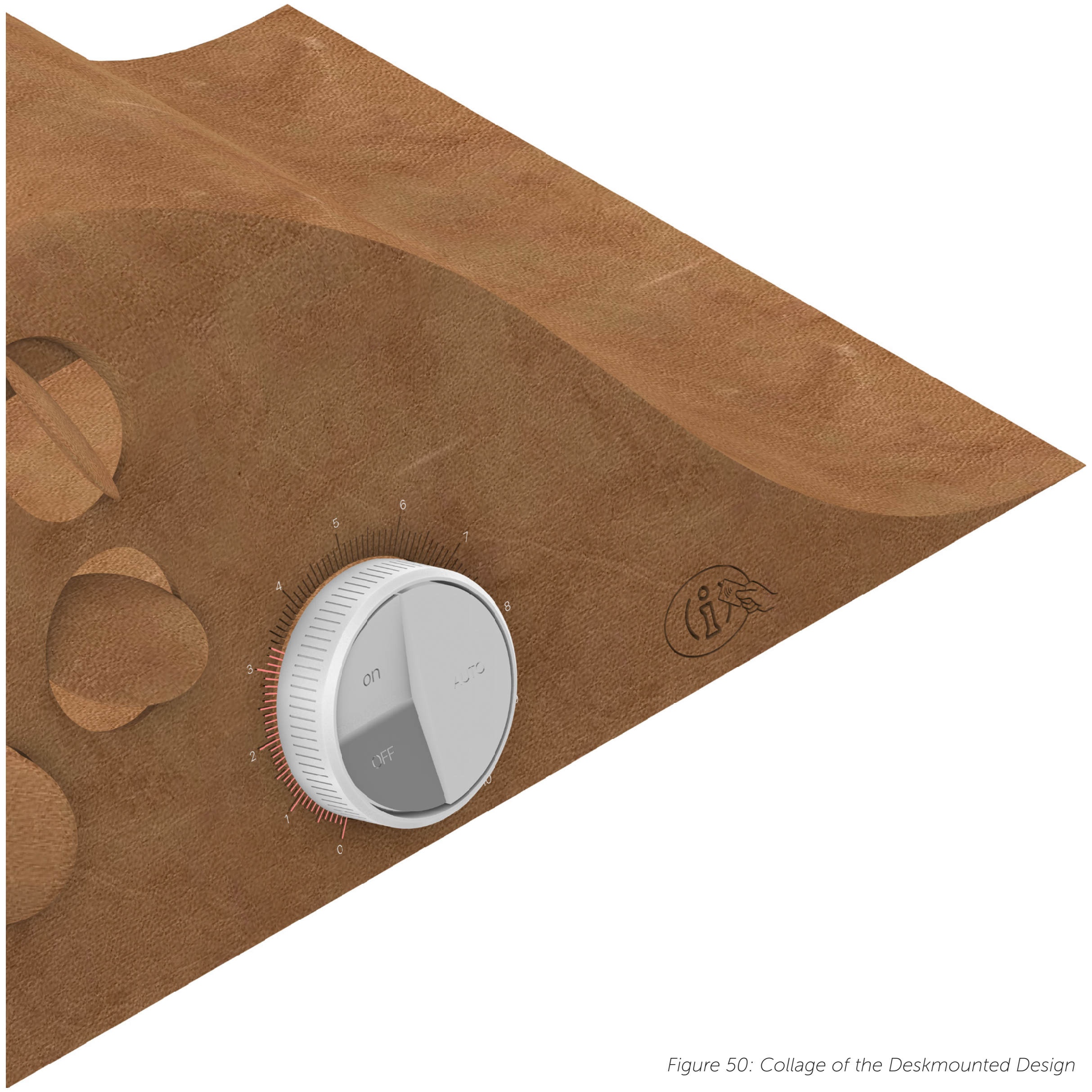
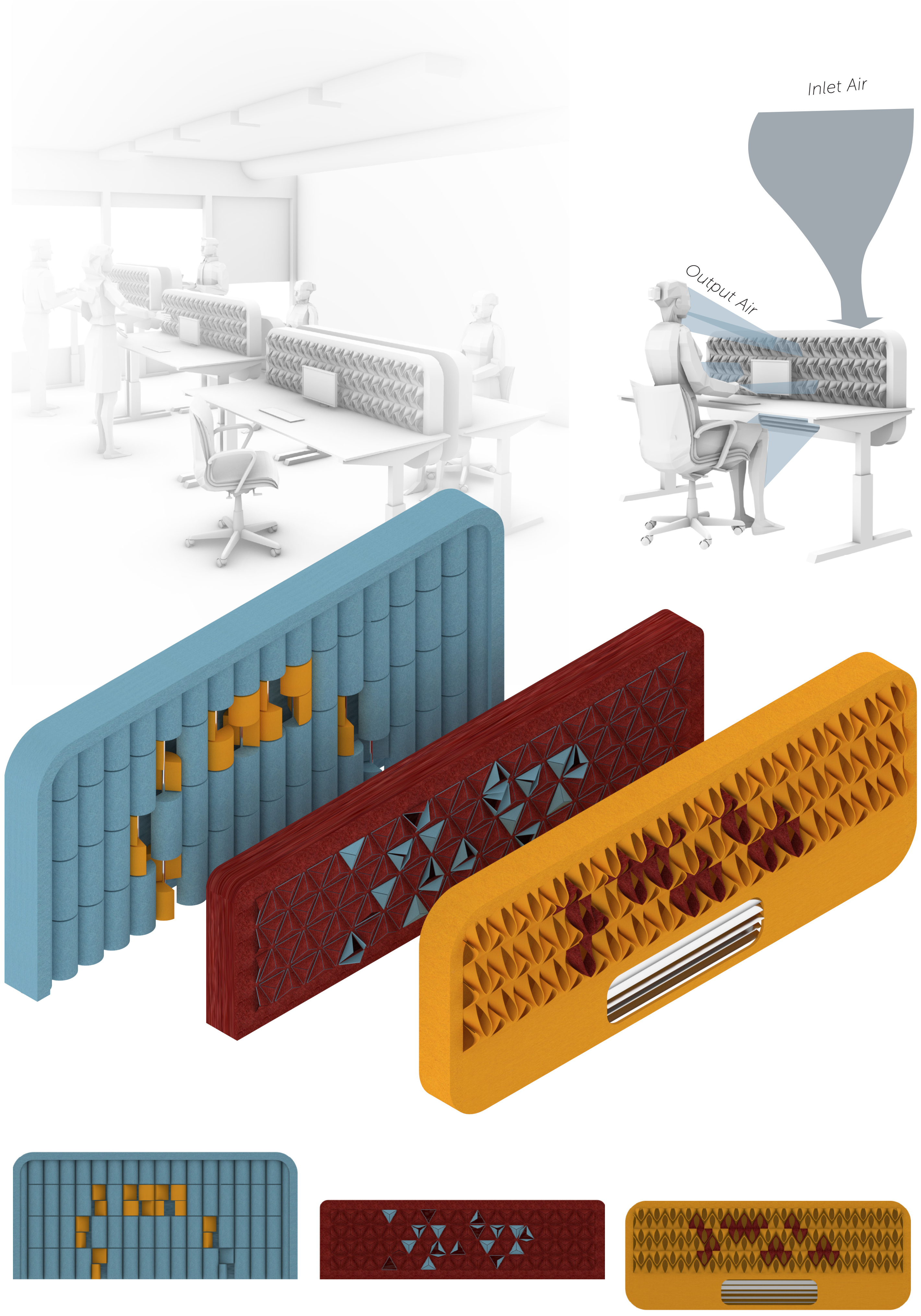


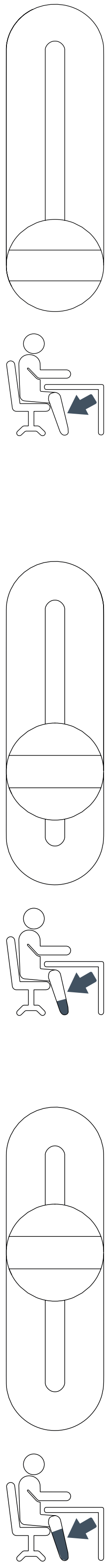
Figure 50: Collage of the Deskmounted Design

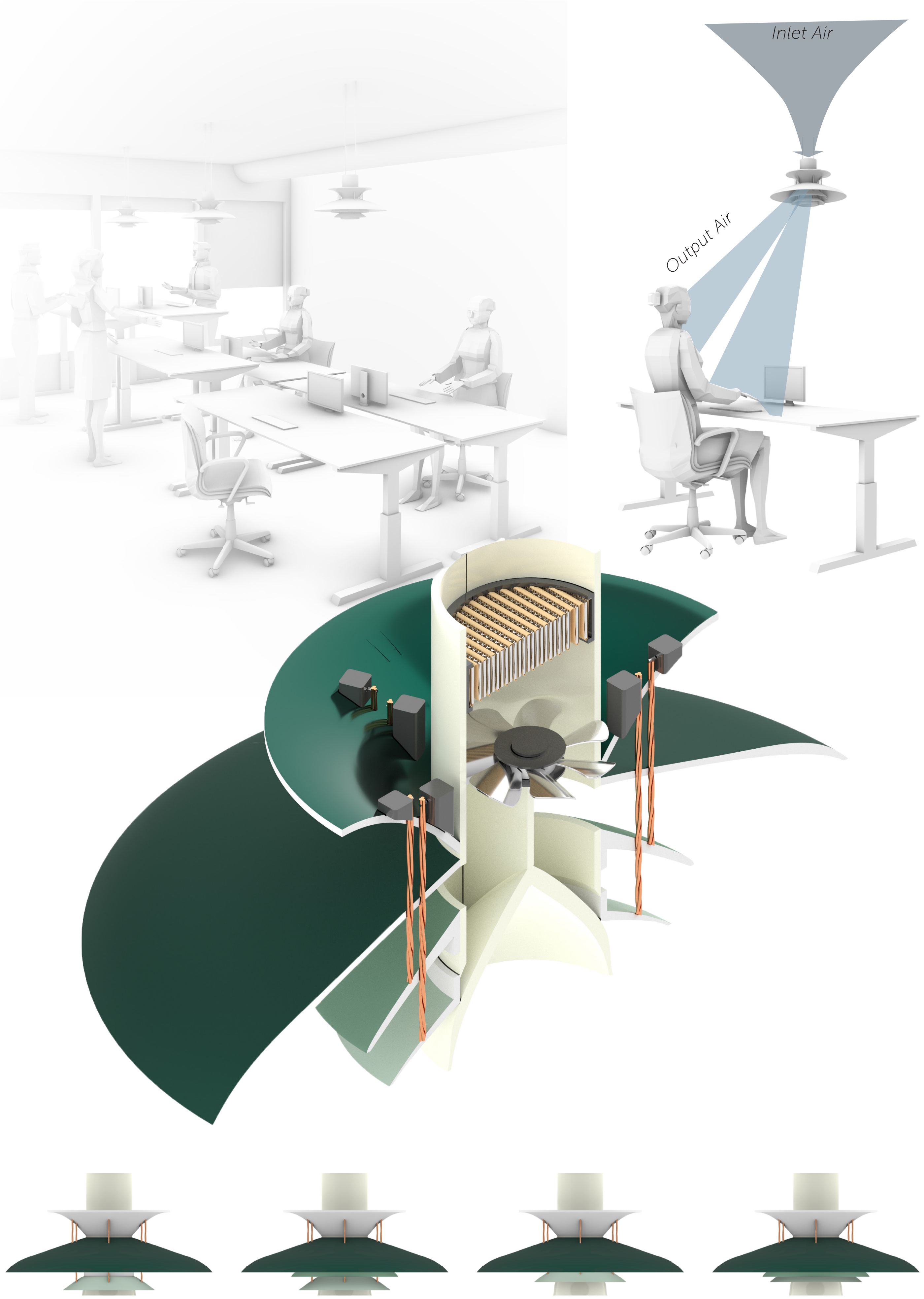


5.2.3 Deks Partition

Here we have three forms of desk partition walls. There's a tall one, blue, where someone can sit quietly behind a partition, a medium-height one where you can still see your neighbor, and a yellow one with the possibility of ventilation. This means an additional control knob is added. On the right, you can see the knobs in different positions. These knobs can change the direction of the panels, determining where you want ventilation. It's chosen here to have variation in different outputs. All the output surfaces correspond to an area related to energy efficiency as mentioned earlier. However, the outputs differ; one output lies within the turning plane, another lies on hinges on the plane, and the third lies outside. Nevertheless, all are equipped with acoustic material. Both the elements themselves and how they're structured relative to each other determine the likelihood of controlling the direction of the airflow. Here, it's very specifically combined with acoustic partitions, which contributes to the acoustics. The partitions are also feasible in other materials such as leather or wood. However, with materials other than fabric, you're limited in that you can't bend them for openings.

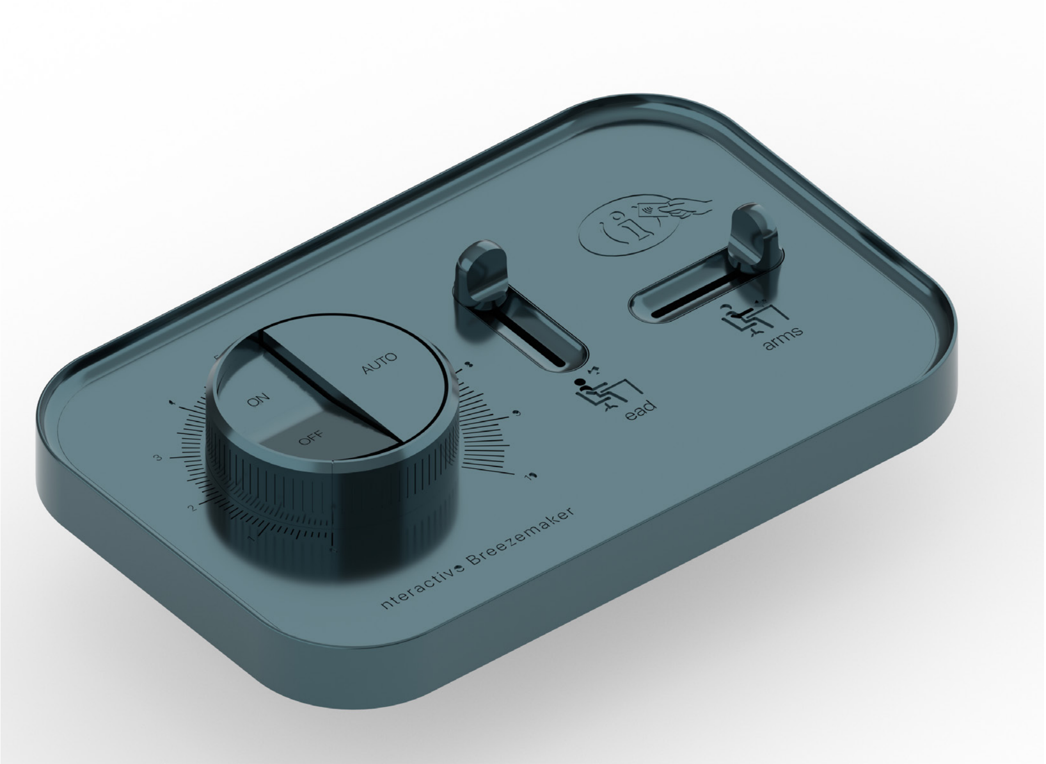
Figure 51: Collage of the Acoustic Partition Solution





5.2.4 Ceiling Mounted

This is not regulated at all but sits diagonally above your head. This option can be combined with a lamp. It consists of a solid core where before the air is sucked in, it is filtered to let in as little dust as possible. The scales around it are based on the angles for both standing and sitting. The scales can move on both sides, and with an interface attached to the table, you can operate it. Because it's outside the 2nd or 3rd ergonomic zone, it is completely controlled via a panel. Again, the dimensions depend on human measurements. The upper movable ring is for the head and the front of the body; sliding it down means it starts at your forehead and more and more wind goes towards your chest downwards. The other slider is for directing wind to your arms. In this case, from your hands towards your shoulders. The reason both elements move like this is because people prefer cooling their forehead initially rather than their cheeks, for example. This often comes from lenses. Additionally, the hands are always exposed, unlike the shoulders, making it effective to direct airflow towards them initially. The lamp is executed in raw steel but can also be executed in other materials such as recycled plastic.



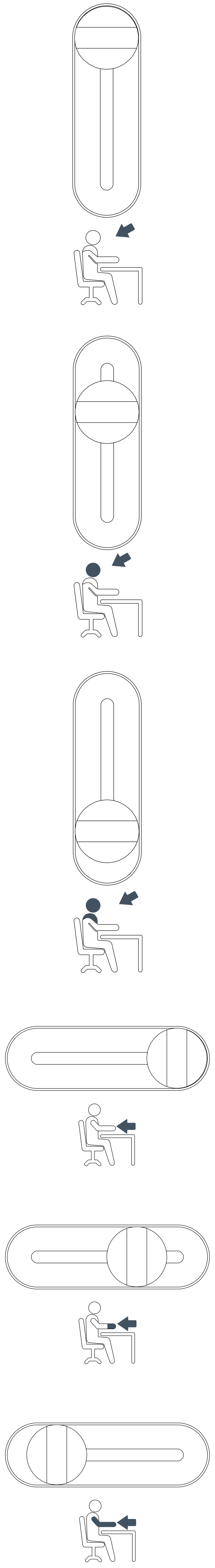


Figure 52: Collage of the light-based solution

1. Which interface do you prefer?

Figure 53

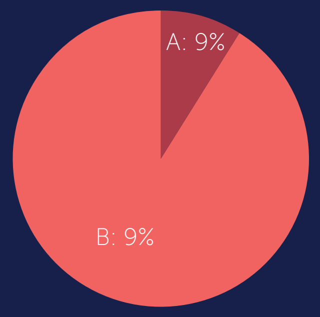


Figure 54

2. Imagine you're feeling too warm and you desire to cool down with a breeze. How would you prefer to utilize the fine-tune button, and what kind of information would you like to receive in response

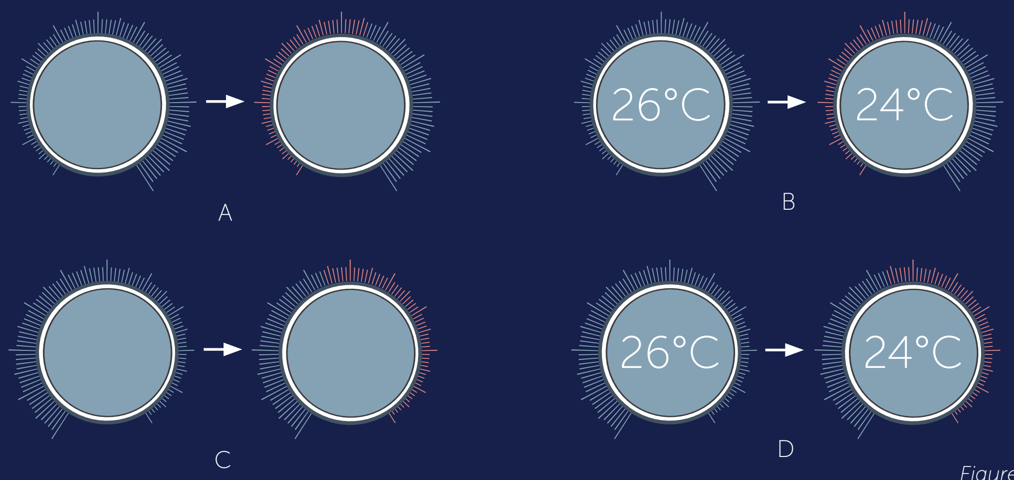


Figure 55

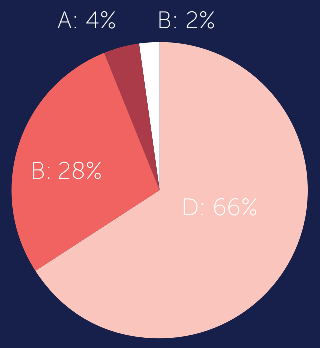
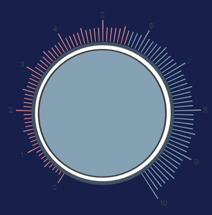


Figure 56

3. If you only had a fine-tune knob, would you want numbers in addition to the scale?



A: yes
B: no
C: other

Figure 57

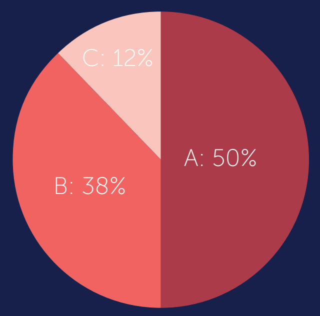


Figure 58

4. If you only had a fine-tune knob and a display that included ambient temperature, would you want numbers in addition to the scale?

A: yes
B: no

Figure 59

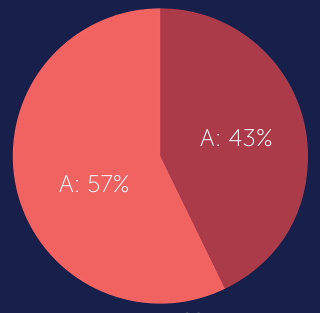


Figure 60

5. If this icon were on the application, what do you think it would mean?

A: provided the right answer
B: provided the wrong

Figure 61

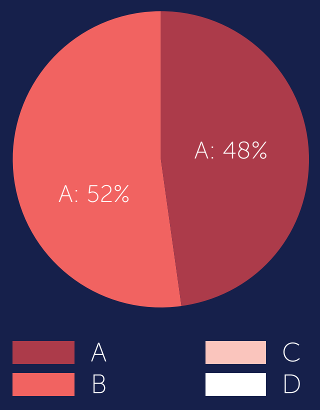


Figure 62

5.3 End-user feedback of the interface

Many steps have been mentioned to arrive at a particular interface. Two main elements in this are: do you give the user the idea of reaching an increased airspeed or do you give the user the idea that you're getting warmer or colder. According to the interviews, users are not interested in the method, it's about the effect. Purely reasoning from the effect, you should not communicate solely in terms of airflow. So for example, not with 1 to 10, but with temperature. Additionally, it was unclear whether the sign of memory capability was clear enough.

After a brief introduction about the project, people were asked which interface they preferred. Just a fine-tune button or a fine-knob with the local temperature. Then the question was: Imagine you're feeling too warm and you want to cool down with a breeze. How would you like to use the fine-tuning button and what information would you like to receive? You could turn the button to the left or right, with feedback provided in the form of a scale of 1 to 1 or a scale of 1 to 10 with a temperature. Then the question was asked if they wanted numbers on that scale bar or not. Following that, they were asked if they wanted a scale bar with numbers when the temperature was also displayed. Ending with the question about what the icon stood for. The questions with their accompanying images are in Appendix F.

This is about validation whether people react more to temperature than just a fine-tuning button. It builds upon the findings from the interviews. Along the way, you can read if people tend more towards 0 to 10 or towards temperature, but this is not explicitly asked. It's about a small, relatively simple validation remotely, where this question wouldn't be appropriate. Namely, whether people respond better to an interface from 1 to 10 or to temperature is something you can't ask, but you have to let people experience it and therefore test it in real life. Because people are expected to think too much instead of it being intuitive.

Ultimately, the small validation was filled out by 47 people. In addition to the questions, the results are also visible. From the first question, it's evident that people prefer to communicate via temperature. After that, if an option is given on how they want to fine-tune, just over half indicate they prefer a fine-tune button that turns to the left. 38% prefer to turn to the right. There's a paradox in that because you increase the airspeed (intuitively to the right), but you decrease the local temperature (intuitively to the left). Solely based on this meeting, you should do it to the left. This could be further validated with a trial.

For one fine-tune button, there's no reference scale yet, except that it runs linearly. The fine-tuning knob with the local temperature already has a reference point. In both cases, it's not entirely clear what deserves preference. A slight majority is in favor, but many people also hesitate. You could interpret this as choice overload.

Finally, regarding the icon for the card. 52% find it clear, 48% don't. Perhaps this is also due to the context and maybe many people don't have experience in specific places where this is often asked, but there is certainly room for improvement.

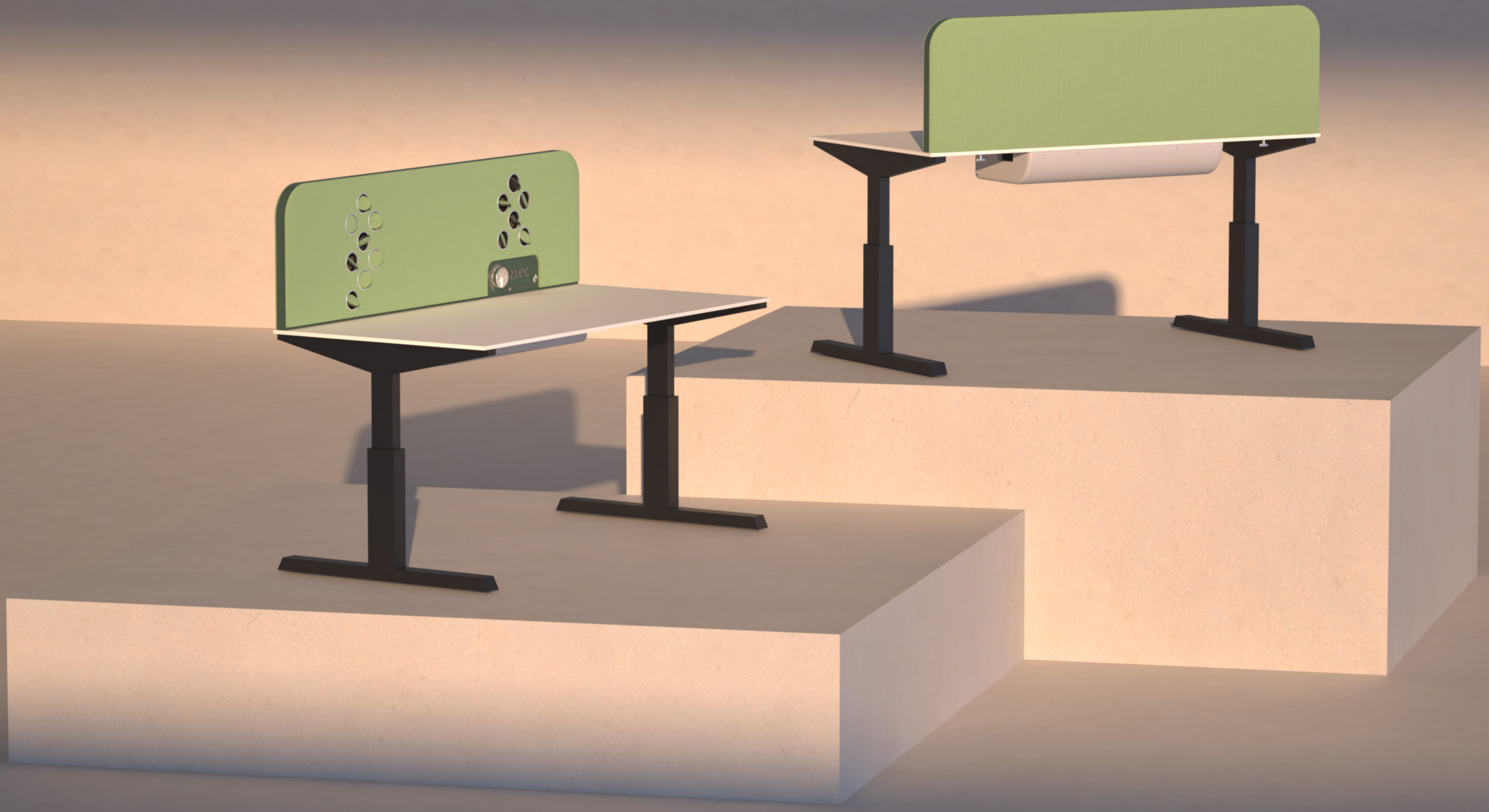


Figure 63: Perspectives on the final design from both front and back viewpoints

5.4 Final Design

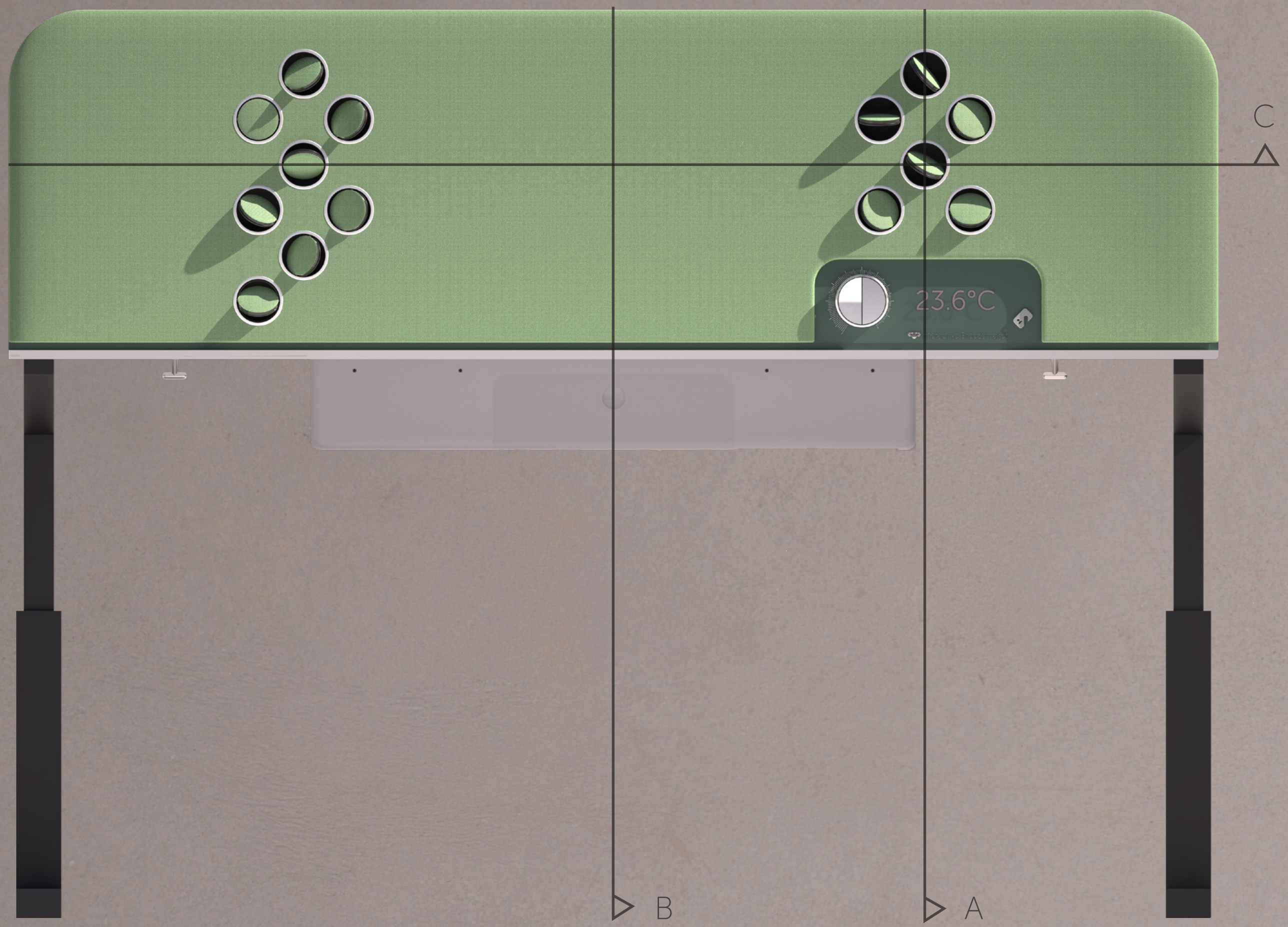
Above, the final designs can be seen from the front and back, attached to a standard model desk that is height-adjustable. On the following pages, the designs are shown in more detail and further explained.

Figure 64: Front view of the final design

Figure 65: Back view of the final design

Figure 66:

Front view



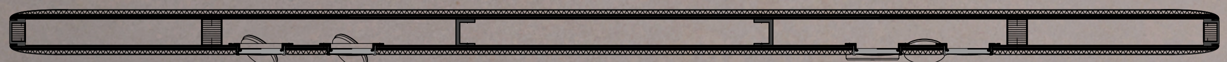


figure 68: section C, 1:10

Figure 67:

Top view


Figure 69:

Back view

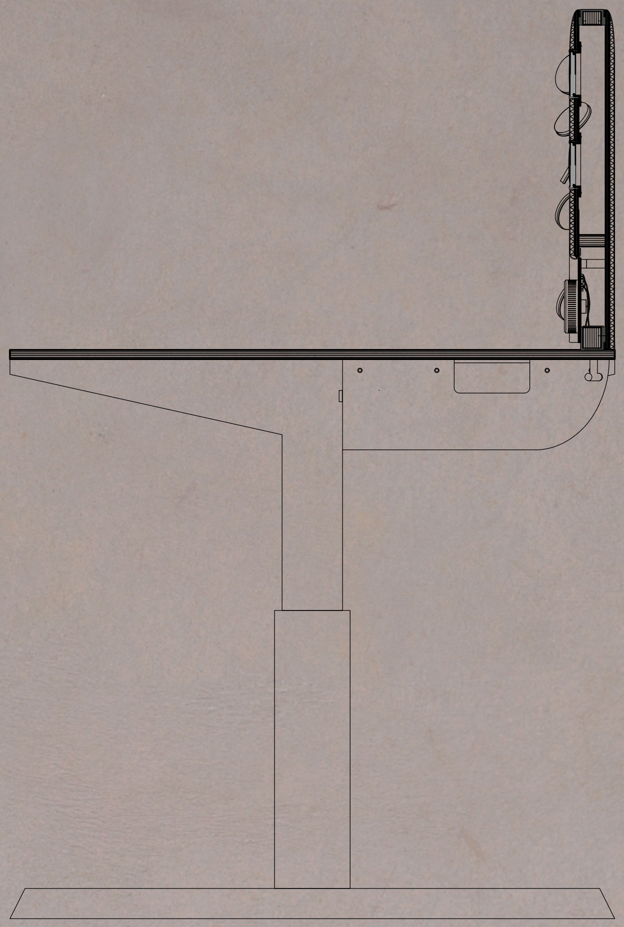


Figure 71: section A, 1:10

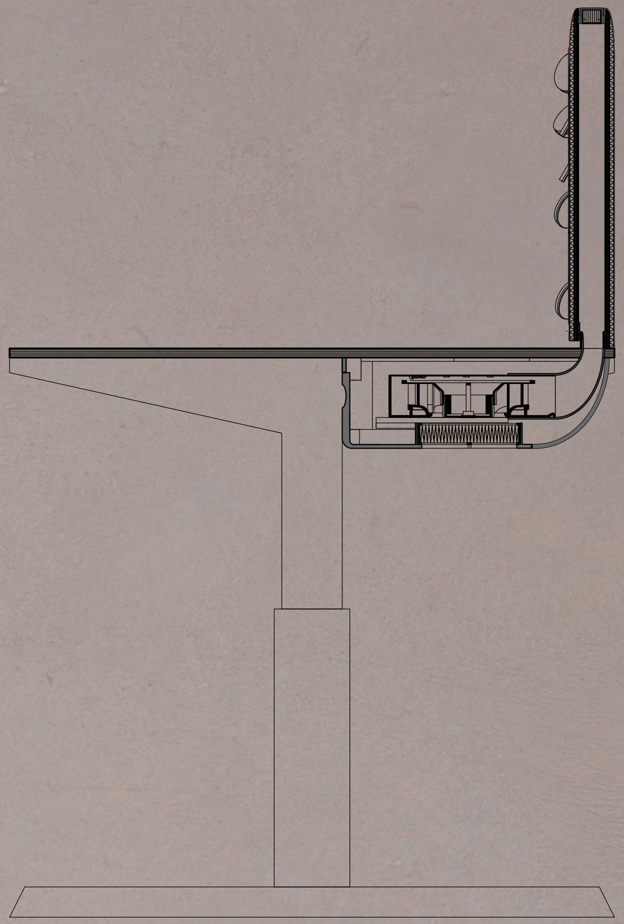


Figure 72: section B, 1:10

On this page, both the views and sections are shown at a scale of 1:10, featuring the device in combination with a standard height-adjustable desk. In section A, the cross-section shows where the interface is located. Section B illustrates the mechanical operation of the system. Section C is a horizontal cross-section.

What is clearly visible in these elements is that the device essentially has two compartments. Namely, the acoustic wall where the interface with the adjustable buttons is located. The air comes from a chamber under the table, where an airtight coupling connects the two elements. The buttons are 360-degree adjustable and airtight. The opening of the buttons corresponds with the energy efficiency of the fan and the entire system.

Before the air is drawn in, it is filtered to improve the quality of the air and primarily to reduce the maintenance of the fan. If the device requires maintenance, the underside of the chamber can be slid out, allowing the filter to be replaced or the fan to be repaired.

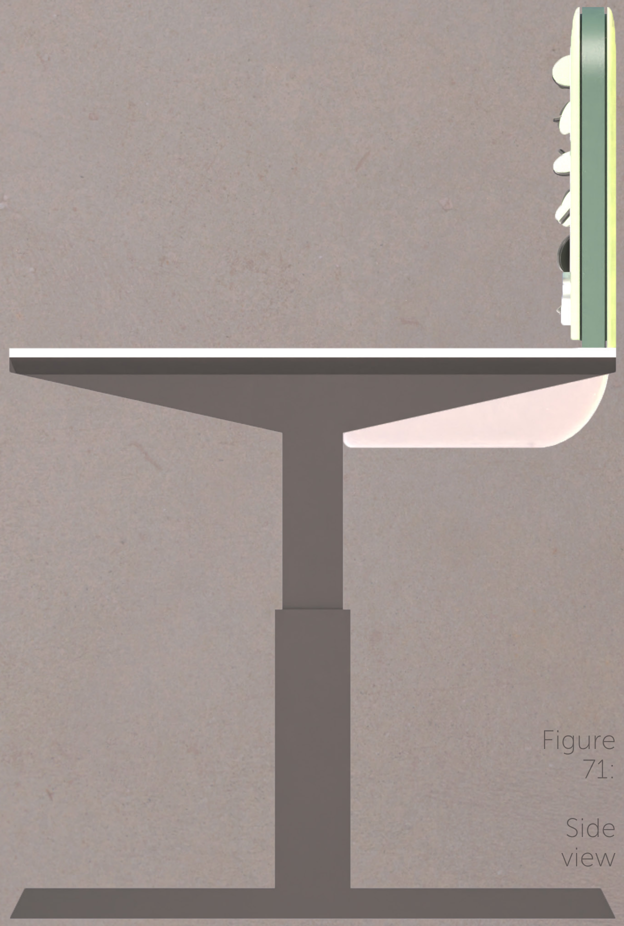
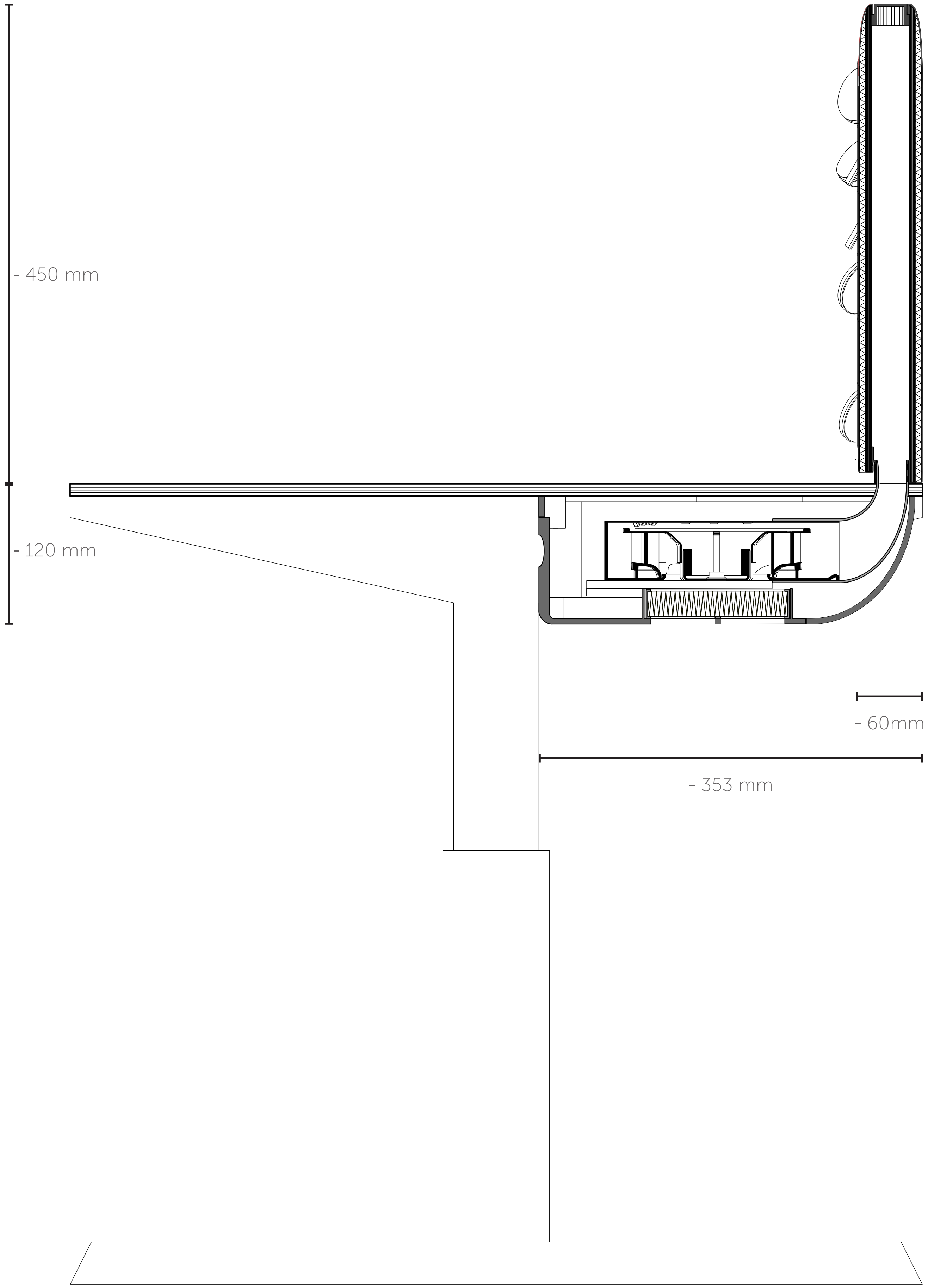


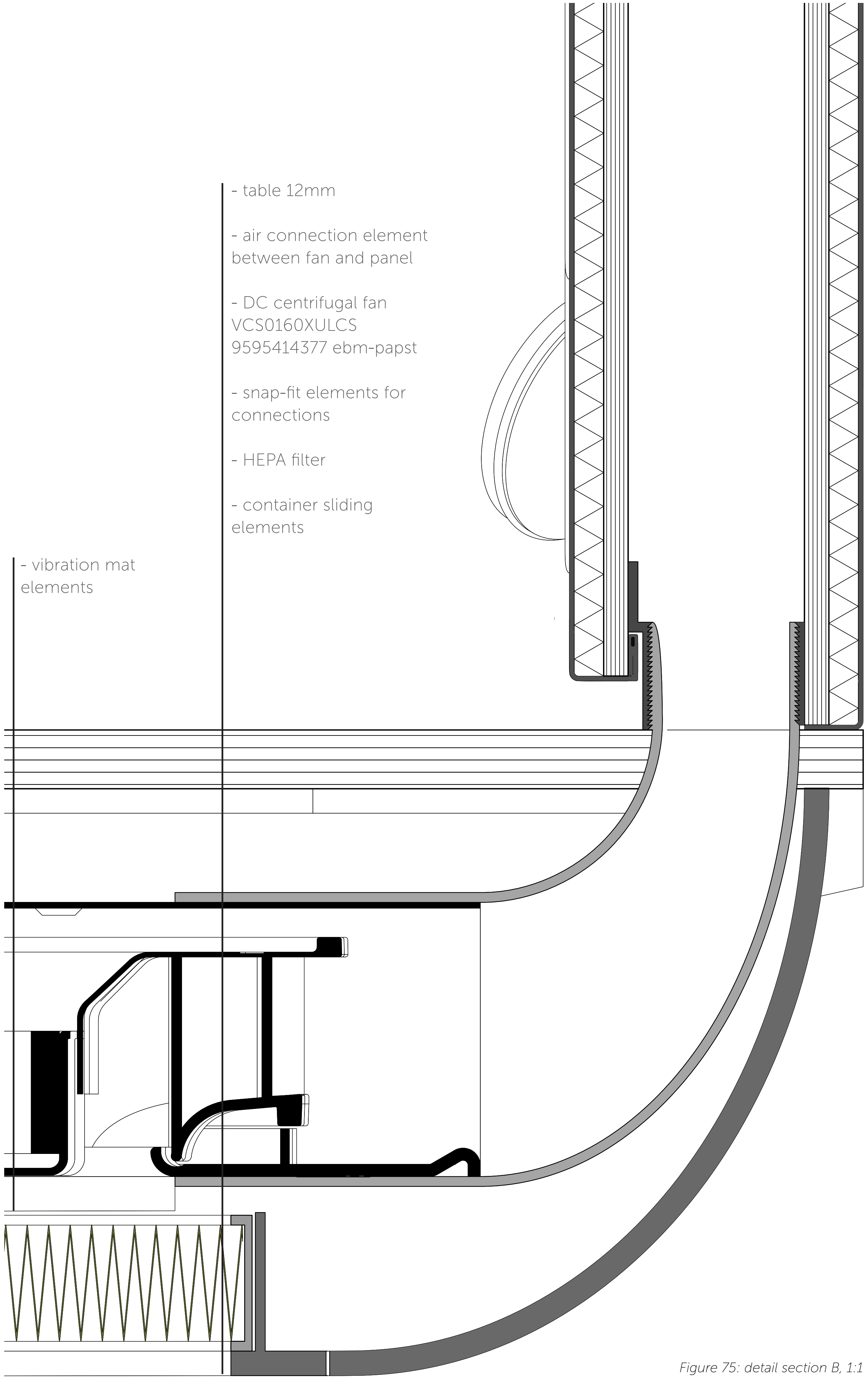
Figure 71:

Side view

Figure 73: Side view

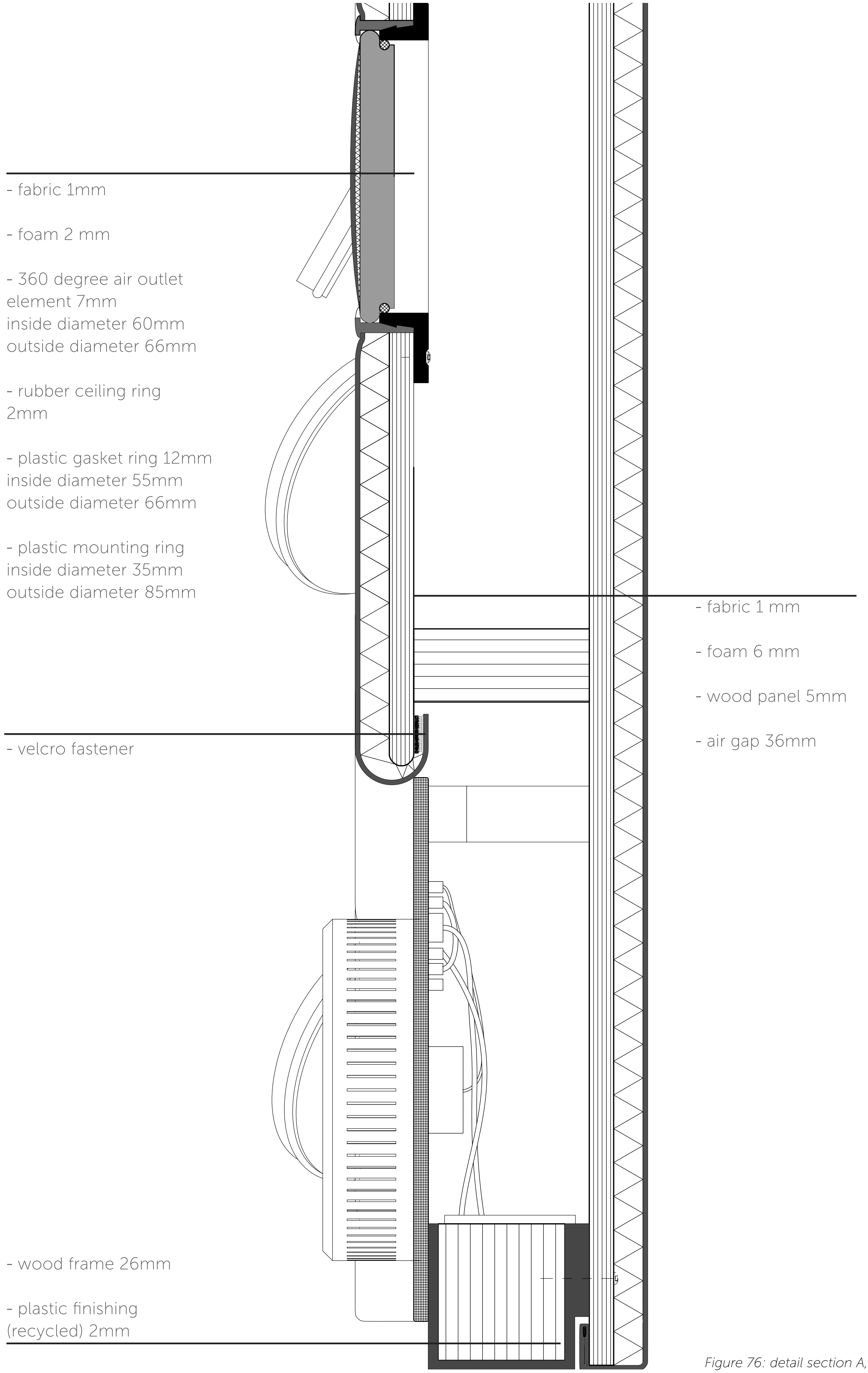


Figuur 74: section B, 1:5



- table 12mm
- air connection element between fan and panel
- DC centrifugal fan VCS0160XULCS 9595414377 ebm-papst
- snap-fit elements for connections
- HEPA filter
- container sliding elements
- vibration mat elements

Figure 75: detail section B, 1:1



- fabric 1mm
- foam 2 mm
- 360 degree air outlet element 7mm inside diameter 60mm outside diameter 66mm
- rubber ceiling ring 2mm
- plastic gasket ring 12mm inside diameter 55mm outside diameter 66mm
- plastic mounting ring inside diameter 35mm outside diameter 85mm
- velcro fastener
- wood frame 26mm
- plastic finishing (recycled) 2mm
- fabric 1 mm
- foam 6 mm
- wood panel 5mm
- air gap 36mm

Figure 76: detail section A, 1:1

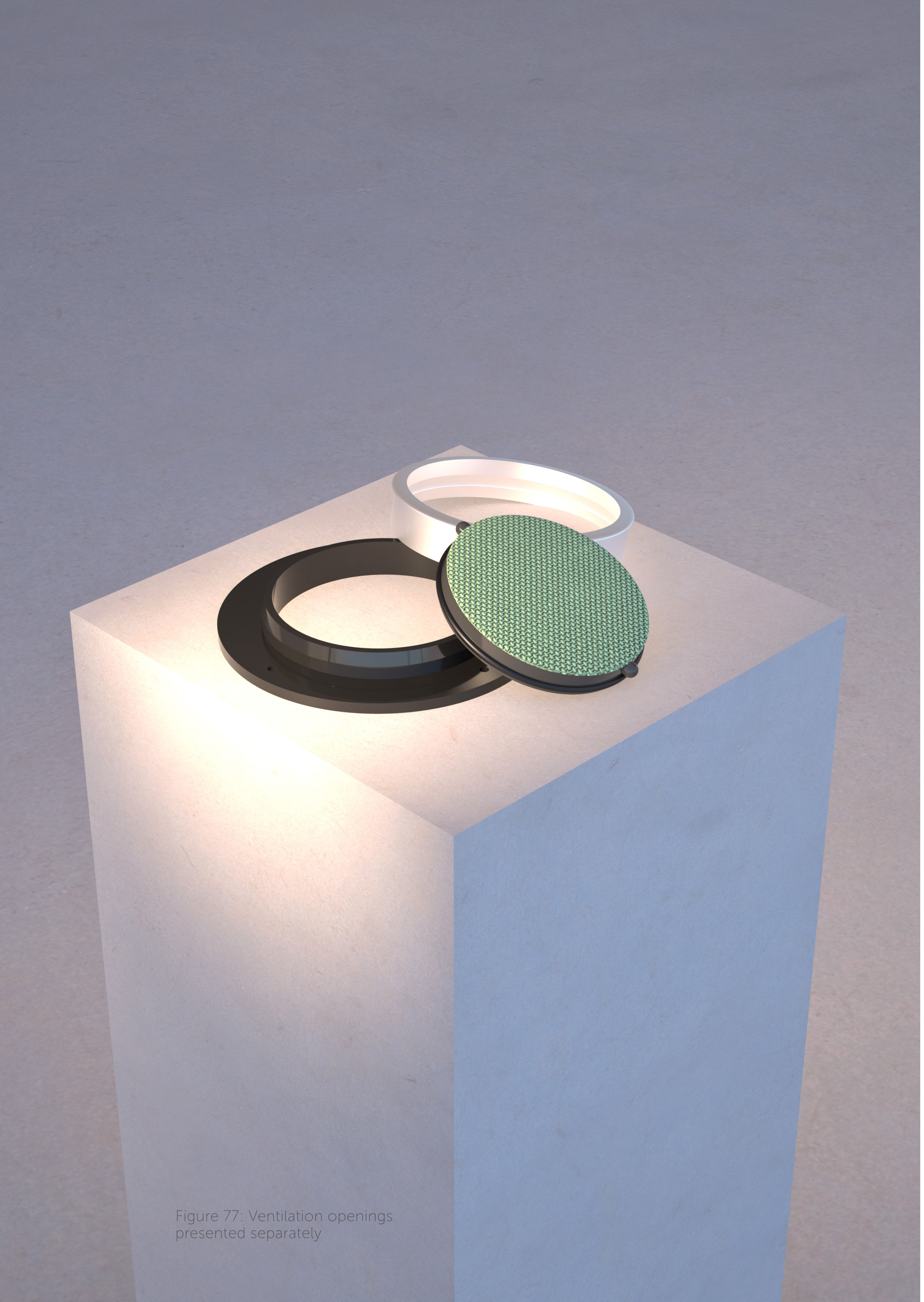


Figure 77: Ventilation openings presented separately

The interface is not just the digital aspect with the fine-tuning knob and other functions; it also encompasses how the movable elements interact with the system. The acoustic panel serves as a pressure box, ensuring that the interior is airtight. The movable elements allow an occupant to direct airflow to desired body parts.

These elements consist of subcomponents, each made from simple parts. The base of the element is a ring that attaches to the hold on the inside. This determines the position of the holes. Next, the adjustable element with two ball heads is mounted onto this ring. The two knobs enable the movable element to act as a pivot point. To effectively manage dust and allow the element to rotate 360 degrees, a ring is implemented on the visible side, ensuring full rotational movement in both directions. This element includes a rubber ring to ensure an airtight seal. Each element can be finished with a fabric of choice, allowing for an integrated design.

All components are simple and can be easily replaced. The elements are designed to be fully detachable, so each part can be replaced at any time. The two rings seal each other with a 'snap-fit' connection.

The images below illustrate the various potential positions for the flap. The black element is inside, while the finishing ring on the outside ensures that the movable element, with its rubber ring and fabric finish, has 360 degrees of rotational freedom.

The fine-tuning is done with the fine-tune button, which is covered on the next page. There, you will also see how the fine-tuning is controlled. Together, these elements actually form the complete interface. In addition to the fine-tune button, there is also an option to link your employee pass or phone where your preferred settings are stored so that you don't have to adjust them anymore. However, you must always adjust the physical movable element according to your preference.

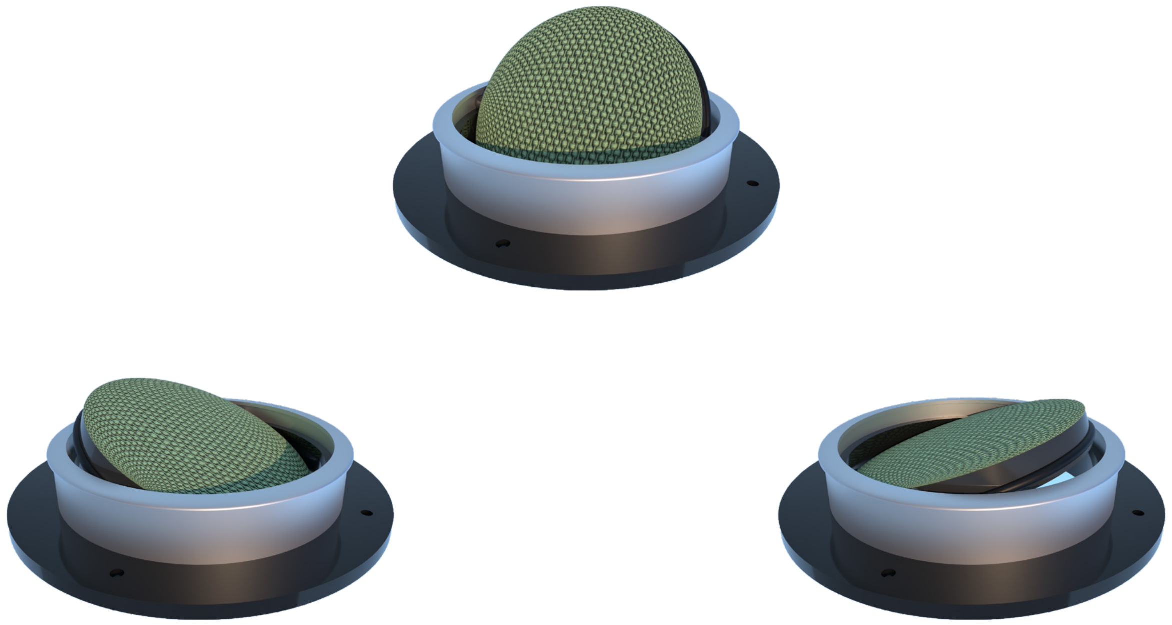


Figure 78: Ventilation openings in various positions

Figure 82: Detailed front view of the final design

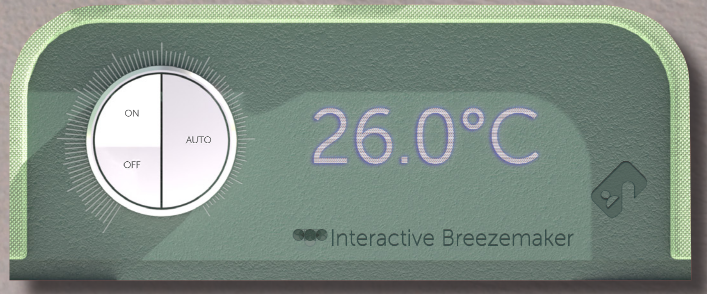


Figure 79: When the device powers on, you first receive a greeting with "HELLO!". Then it displays the local operating temperature of your workspace.

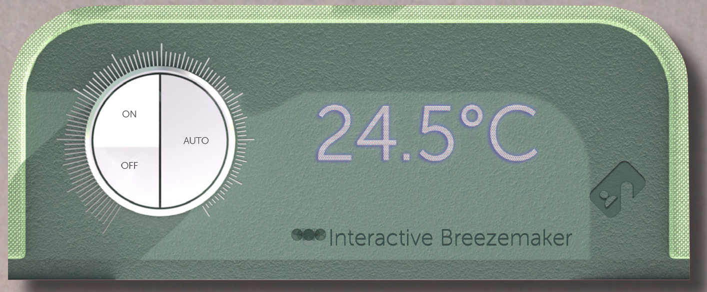


Figure 80: Next, you can switch it to the desired local temperature by turning the fine-tune button to the left, thereby increasing the airflow speed. You will receive visual feedback from the system and tangible feedback from the fine-tune button.

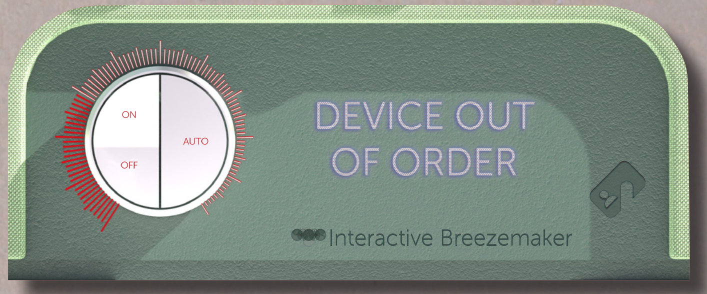


Figure 81: If the device is broken, you will receive a message stating "device out of order" and you should inform your facility manager.

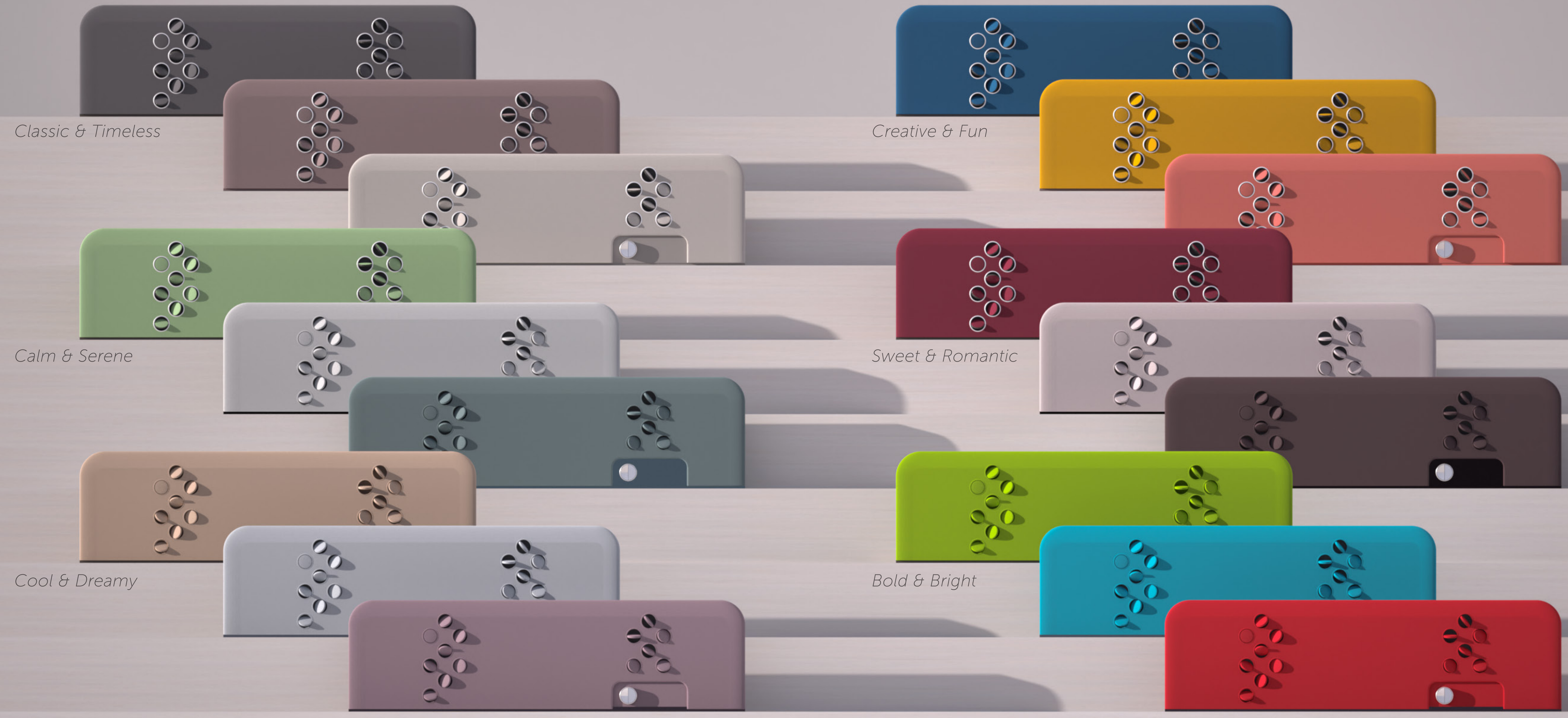


Figure 83: Overview of different designs with various color options

As discussed in the framework, customizable design options are incredibly important for an interior architect. There are various choices available for color combinations. Both the fabric and the synthetic frame finish can be obtained in different color combinations.

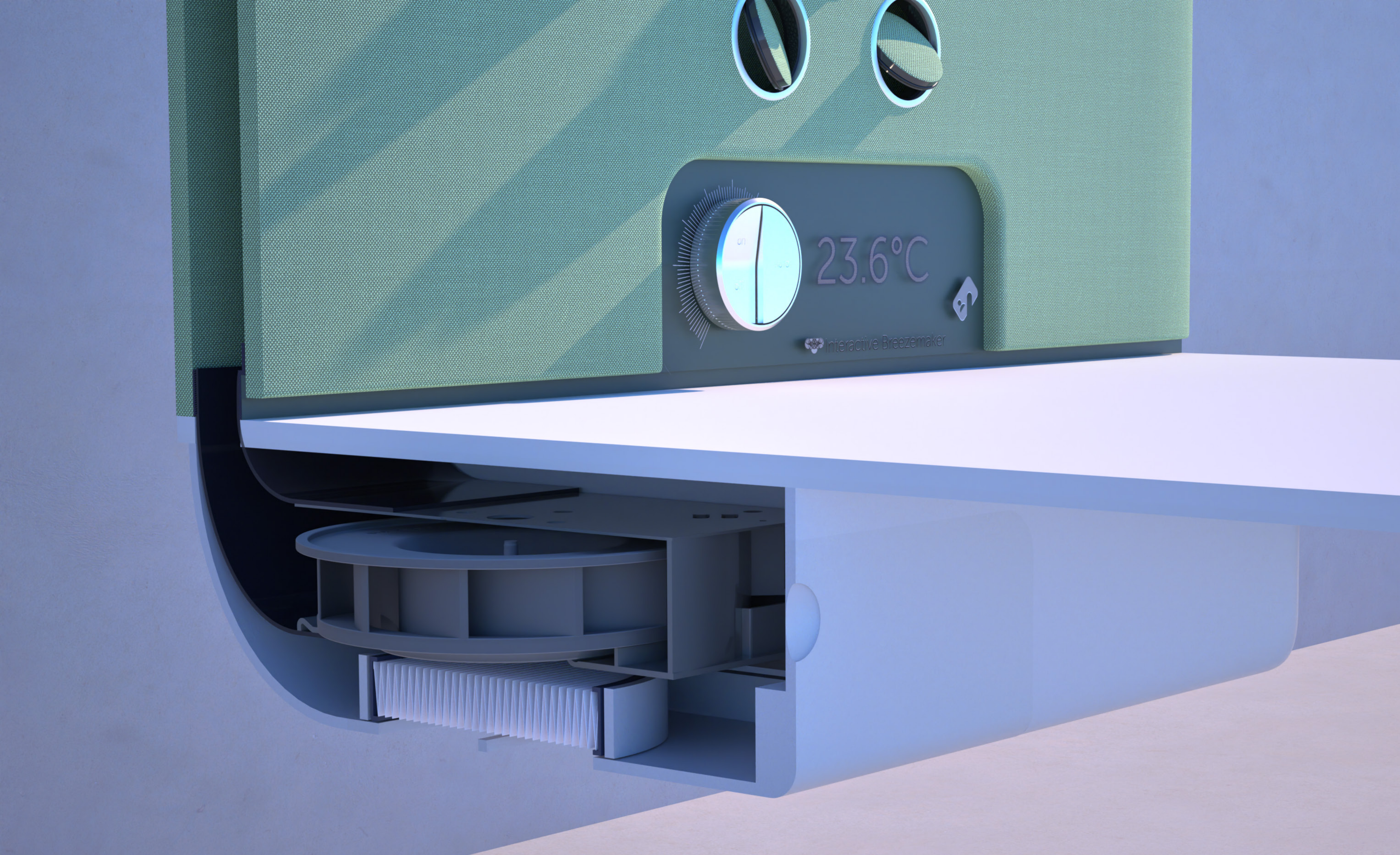
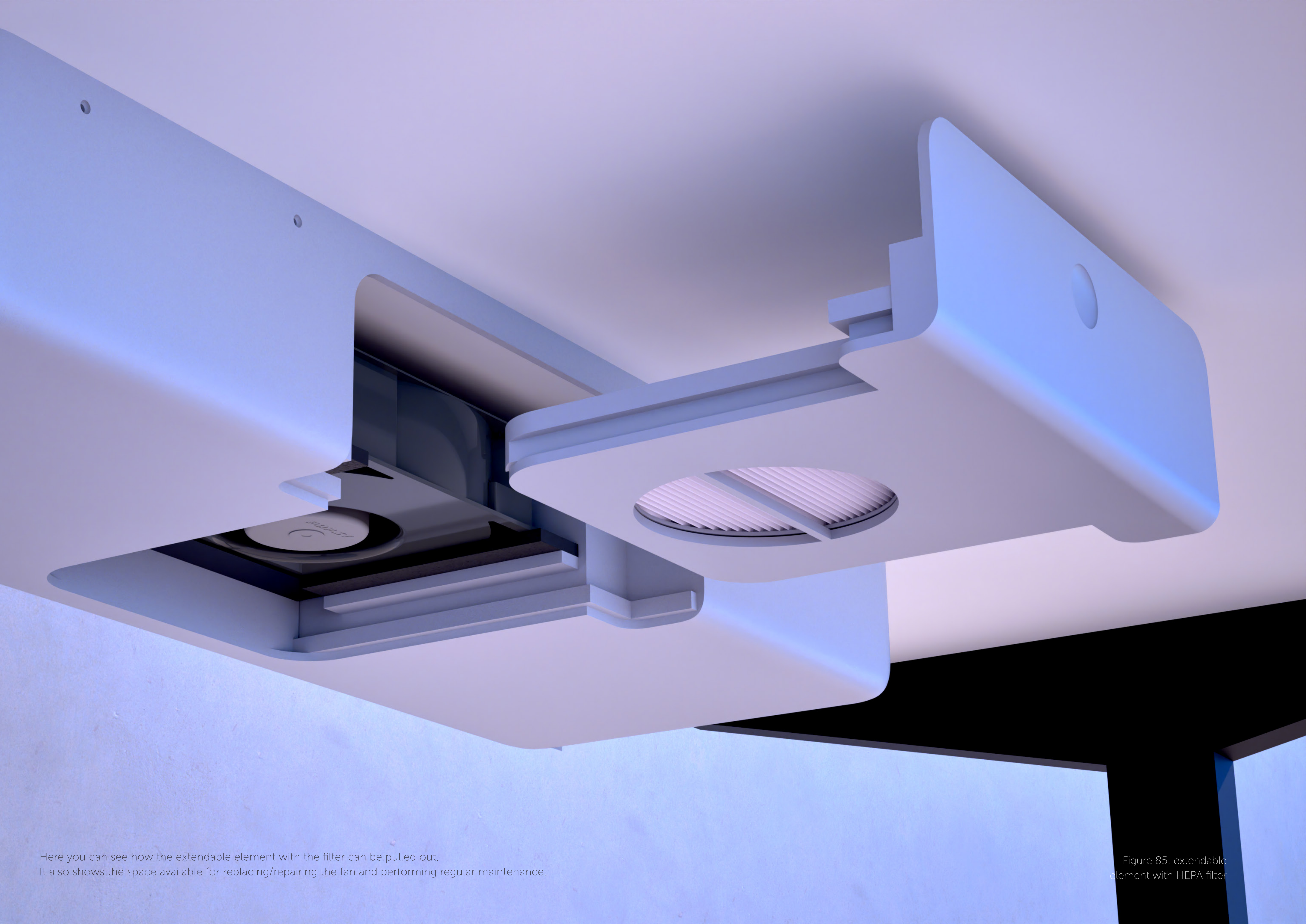


Figure 84: Section of mechanical characteristics of the system

Here is a cross-section showing the heart of the system. It starts with a drawer that is extendable, containing a replaceable HEPA filter. Through this HEPA filter, the air is pulled upwards by the centrifugal fan, after which it passes horizontally through the connection from the lower compartment to the acoustic panel, where the air eventually reaches the occupant through one of the openings.



Here you can see how the extendable element with the filter can be pulled out.
It also shows the space available for replacing/repairing the fan and performing regular maintenance.

Figure 85: extendable element with HEPA filter

Figure 86: Interactive Breezemaker integrated in open-plan office

Figure 87: Interactive Breezemaker integrated in open-plan office

Figure 88: Interactive Breezemaker integrated in open-plan office

5.5 Discussion & Conclusion

The final chapter builds upon the framework outlined in Chapter 4. In doing so, the design criteria, requirements, and considerations were utilized. All of these elements contribute to addressing the question: How can we effectively integrate a breezemaker application into open-plan offices? All mandatory criteria are important, so where do you begin designing? These criteria represent individual functions, thus they serve as sub-functions of the design. Through the morphological chart method, various variants were generated for the potential physical implementation of these sub-functions. These designs were all assessed using the Harris profile. This chapter primarily transitions from abstract terms to tangible elements.

It was decided to proceed with three main concepts in this thesis. The first two, the desk-mounted and the partition wall, received the highest scores. The third main concept that was pursued did not score the highest, largely due to the presence of an option in the 3rd ergonomic zone, just behind it, and one completely outside of any zones. Furthermore, interviews revealed that for large spaces, ceiling-mounted options are less desirable, but they might work well for smaller spaces. After considering three design concepts, it was decided, in consultation with experts, to proceed with the partition element to develop it into a final design. The partition was deemed the most generic and suitable solution for accommodating flexible workspaces with one fixed PC screen.

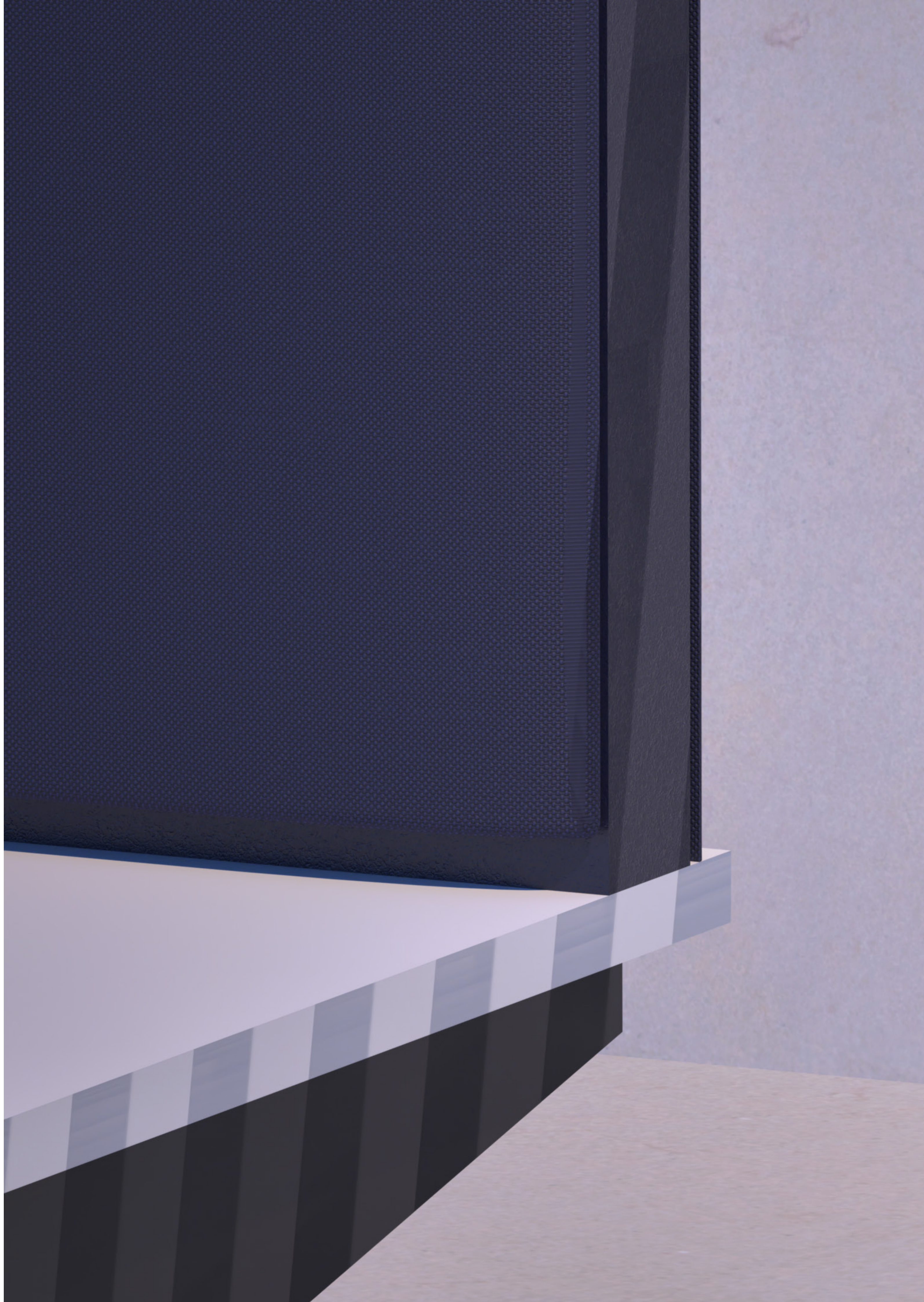
All three main concepts have the same interface based on physical buttons. Each features a power on/off button and an automatic preset function. Fine-tuning is based on hand ergonomics with an optimal size and is continuously adjustable from 0 to 10 or based on the operative temperature. The system provides both physical and tangible feedback when it is operational and visual feedback when maintenance is required. Additionally, the soft criterion is incorporated, allowing users to set preferred settings online by placing their pass on it.

In the case of the desk-mounted solution and acoustic partition wall, the airflow direction is determined by physical elements attached to the device (3rd ergonomic zone). These buttons are determined by the designer and cover multiple sizes. In the case of the ceiling-mounted solution, the wind direction is regulated by buttons.

The interface was validated in a specific section through a small online survey with 47 respondents. They expressed a preference for receiving an indication of the ambient temperature and adjusting it, rather than a scale of 1 to 10. It was unclear if users wanted to lower the temperature by turning the button to the left, indicating a decrease in temperature, or increase the airflow, which would mean a movement to the right. Despite reaching a final design, it would be beneficial for further research to test an application. To truly achieve intuitive switching, a device that works with various interfaces is necessary. Only then can it be determined what works best for people. When using an interface of a drawing, people tend to overthink, which diminishes intuitiveness. Furthermore, it could be further validated what people find pleasant in terms of openings to direct the wind towards them. Additionally, a functional test setup could be evaluated based on design criteria, considering sound, draft felt by other occupants, and how precisely the wind adjustment per body part is.

This illustrates that a fixed workflow during the design process wouldn't suffice. It's more systematic to continuously develop all subfunctions to reach a final design. The final design also meets all requirements set in the design framework. Moreover, the basic element, the partition, is not much different from a normal acoustic partition. It's mainly about the adjustments on the inside with the connection at the bottom of the desk where the fan is located. Inside the wall, there are prefab air-tight heads that enable airflow in 360 degrees. It's airtight in theory, but whether it's truly airtight and if it achieves the desired air throw would need to be determined through an experiment. Similarly, the type of fan required to deliver the necessary m3/h, in combination with the static pressure of the system, needs to be determined. Despite a potentially complex cross-section and combination of elements, it's possible to produce this easily and in bulk for large-scale implementation in open-plan offices.

In conclusion, the effective integration of a breezemaker application in an open-plan office involves developing all design requirements and considerations as separate subfunctions and organizing them in a matrix format to then evaluate them against the specified design criteria. However, there comes a moment when everything is brought together, and at that point, it's crucial to understand the scale and context well when evaluating the designs. Simply put, an open-plan office doesn't specify how many people work there. The level of detail differs when designing for an office of 40 versus 1000 people. Therefore, it's essential to minimize the impact of your device on the rest of the office layout and always strive for a balance where the device blends into the environment while still challenging the user to use the application.



06

DISCUSSION

Addressing the research problem of designing an effective method for increasing airspeeds and air distribution individually controllable in open-plan offices in a temperate maritime climate, integrated as a building product, necessitates a thorough exploration of various factors influencing thermal comfort, user control preferences, application effectiveness, integration challenges, and design considerations.

Firstly, the effect of increased airflow on an individual's thermal comfort was revealed. It involves working within operative temperatures between 24 and 30 degrees Celsius, with relative humidity between 40 and 60%, a work activity level between 1 and 1.4 MET, and clothing level between 0.5 and 0.6 MET. The air speeds required to achieve the right comfort level range between 0.23 and 1.5 m/s. Besides these factors, the type of wind is also important, with a power spectrum closer to $\beta \approx 1.8$ rather than ≈ 0.60, and a turbulence intensity between 40% and 60%.

Personal control over applications providing elevated airspeed emerged as a central aspect influencing user experiences in open-plan office environments. Understanding users' perceptions and preferences regarding control customization is essential for designing effective control systems that enhance comfort and productivity. This fits within the idea of thermal comfort, where everyone's comfort level varies due to age, gender, origin, and adaptive measures are necessary to regulate it.

With those experiences and expectations, it is also important to bear in mind that there are primarily two types of people: one with a strong locus of control and the other with a strong internal locus of control. The effectiveness of control lies in the eventual behavior of the user. This effectiveness is partially derived from understanding the experiences and expectations of the user, but also the limitations imposed by maintenance personnel, managers, interior architects, investors: the social and building environment.

A comparative analysis of various airflow enhancement applications highlighted the advantages and disadvantages inherent in different strategies. From this comparison, it became evident that all systems concentrate on a single domain rather than encompassing the entirety of the scope. While existing solutions vary in design orientation, a comprehensive evaluation is necessary to determine for the domains of performance, control capabilities, and robustness. In all three domains, there were factors where the implementation remained unknown, and validation was also necessary to see if certain elements mentioned in the literature were indeed applicable for a personalized comfort system based on airspeed.

Through interviews, these factors were validated and specified, with some new factors also emerging. Efforts to integrate breezemaker applications within open-plan offices underscored the complexity of the endeavor, requiring careful consideration of technical, ergonomic, and aesthetic factors. User-centric design principles and engagement with stakeholders from diverse backgrounds are essential for developing solutions that enrich the workplace experience while enhancing comfort and productivity. The most important aspect here is the hierarchy of these factors relative to each other.

Building upon the insights gathered, a coherent framework was developed to guide the integration of breezemaker devices. The framework incorporates the three design drivers: control, performance, and robustness, delineating which elements must be incorporated and which could be integrated. Thus, there is a certain hierarchy among these factors. Additionally, the factors in the "must" group are sometimes of a different nature. For instance, visual and tangible feedback is more comprehensive than implementing an on/off button. To facilitate systematic design, the "must" group is divided into design criteria and design requirements, where the design criteria can govern the requirements. The "should" group is regarded as considerations.

Further exploration through concept development and evaluation revealed promising solutions, such as desk-mounted and partition wall configurations, with intuitive interfaces and customizable airflow options.

In earlier discussions and conclusions, the sub-questions have already been addressed, and now is the moment to discuss the underlying theme. By defining and segmenting various areas, a clear framework is developed in which the necessary factors need to be implemented. This framework demonstrates meticulousness and expertise, yet its value lies in also shedding light on the design process. These two aspects are interlinked.

For instance, consider the identification of various personality types in the literature, such as individuals with strong internal and external locus of control. Interviews reveal that individuals with an internal locus of control are inclined towards functions with on-off switches and a fine-tuning option, whereas those with a strong external locus of control prefer an automatic setting that relinquishes control. It is not only important to identify these factors but also crucial to consider how to implement them. This includes aspects like visibility, range, reading direction, hand ergonomics, and what should be clear initially.

This underscores the importance of clearly defining the scale level throughout the research. The study falls under the overarching category of indoor environmental quality, followed by thermal comfort, specifically adaptive thermal comfort. An example of this is a "breezemaker" device as an effective adaptive measure.

Perhaps the outcome of the research contrasts with the overarching umbrella under which it falls. Adaptive thermal comfort entails widening the bandwidths and having more effective adaptive measures available in buildings, allowing occupants to adjust according to how they feel. Feel, it about how you feel in buildings.

Perceived control is rooted in experiences and expectations. Currently, these experiences show that people heavily rely on quantified information from research for their climatic situation. In various scenarios such as a car situation, smart building systems, or a more illustrative example like a digital watch displaying environmental parameters such as temperature, perceived temperature, sound level, and other environmental factors, we observe the integration of technology into our daily lives. For instance, during inclement weather, instead of looking outside to check if it's raining, we often rely on our mobile phones with rain radar apps. This gives people a sense of control. It appears to be a trend that people increasingly trust quantified information over their qualitative feeling. On one hand, adaptive measures aim for people to rely more on their feeling, but on the other hand, effectiveness at present involves adding quantified information. This observation also implies room for future changes, as experiences and expectations can evolve.

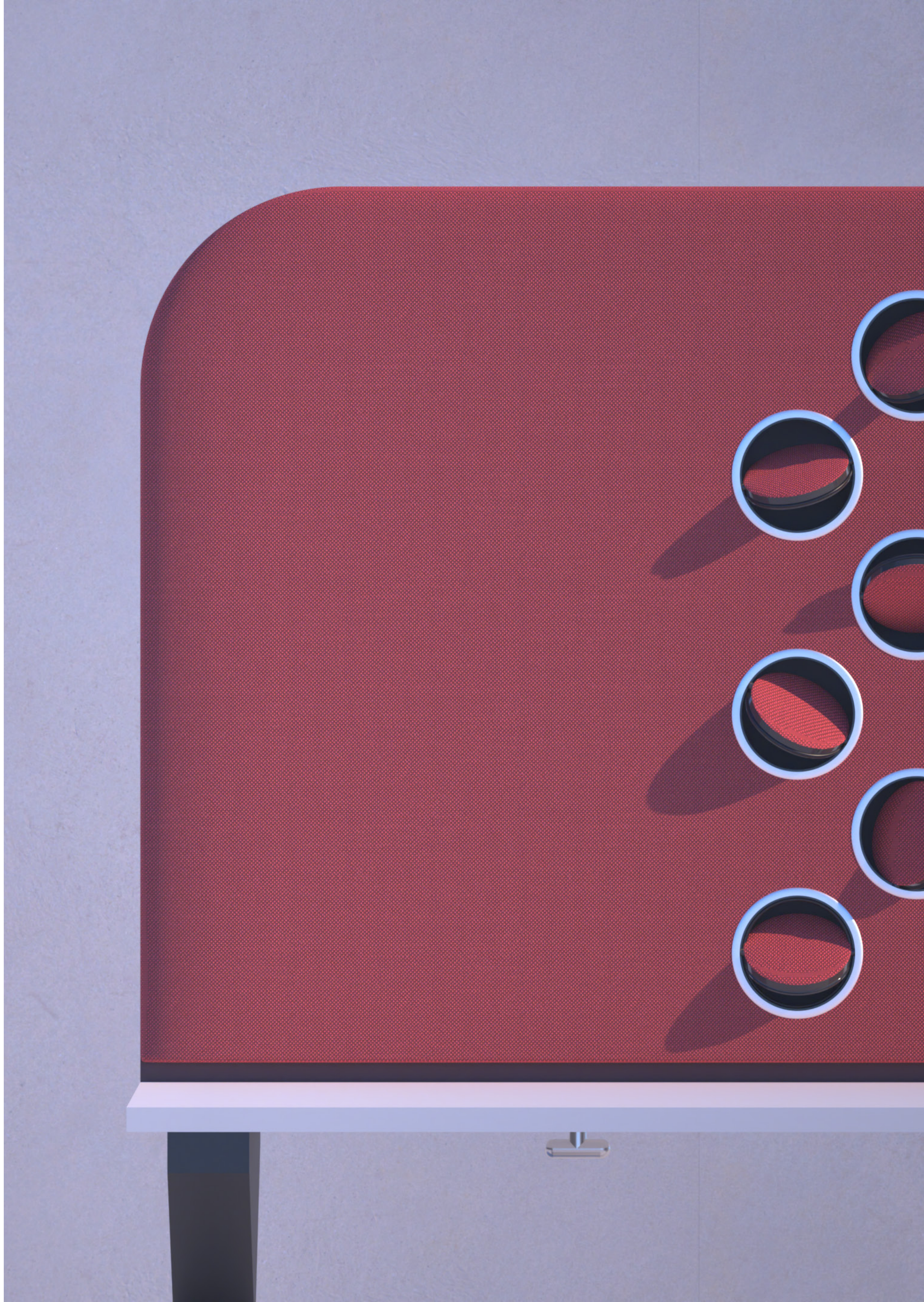
Validation through focus groups or experimentation is necessary to confirm the effectiveness, energy efficiency, and sound levels of these designs. Another important consideration is the interview method. The interview was semi-structured to minimize biases and promote an open conversation. Validated factors emerged from this, but also new ones, and it became evident which factors need to be addressed before being accepted by both experts and end-users. This would not have occurred naturally if the interview had been highly structured. It would now be interesting to have another group of respondents assess if this hierarchy is also valid.

Above are all the sub-factors described that are important for effectively implementing personalized airflow for office spaces in the summer. The research begins with the desire to work within wider temperature ranges, which in the summer means higher indoor temperatures. To remain comfortable and productive, it was decided to achieve this by increasing the airspeed. Through broad research, the results are not only focused on technical engineering but also interior architecture and human-centered design aspects.

Answering the question of how to effectively apply personalized airflow for thermal comfort, it is important to understand the experiences and expectations of users of open office spaces, as well as the involvement of various experts in the design process. These together define the boundaries. In this research, these boundaries have been translated into requirements such as noiselessness, no draft for other users, precise adjustment per body part, visual and tangible feedback on operation, must not hinder the flexibility of the office, and where the primary control is in the form of a physical interface. This control can be manual for people with a strong internal locus of control, or automatic for people with an external locus of control. The fine-tuning should be easy to understand and maintain, and based on the ergonomics of the human body. The airflow is minimally directed towards the arms and forehead, and the device should be located in the third or later ergonomic zone, while the control point is in the second or third ergonomic zone.

This research forms a basis for further research in the area of personal environmental control systems. This research focuses on a summer situation and using increased airspeed as a means. There are still numerous other factors such as winter situations, but also acoustics and light and air quality that could also play a role, especially focused on the workplace. The methodology in this research can serve as a guideline for outcomes in other areas. In addition, on a construction level, further investigation can be carried out to see if there is an opportunity to connect this to central systems without losing flexibility. Furthermore, the interface could be further examined with input from experts in industrial design to develop and validate the conditions set out in this research. Additionally, in the direction of mechanical engineering, an interesting question would be how to achieve wind speed more effectively without making noise.

In the built environment, it is not self-evident that when there is a connection between humans and technology, one should not only control the technical aspect but also the human aspect. Looking at the conclusion, it appears to be crucial to have a good overview and balance between the various factors. It is indeed evident that people desire their climatic conditions to be simply managed; they don't want to be overly preoccupied with it. However, achieving thermal comfort requires interaction with its user. Effective adaptive measures can be likened to the synergy of a bicycle and its rider. Bicycles can exist without their riders, and riders without their bicycles, but the interaction between the two creates a unique system and process.



07

CONCLUSION

In this study, an attempt was made to answer the main question:

How can we develop an evidence-based framework to implement personalized air velocity for occupants in open-plan offices during summer and design an effective solution?

To address this question, the following sub-questions were answered:

What is the effect of increased airflow on an individual's thermal comfort, considering parameters such as metabolic rate, clothing level, radiant temperature, air temperature, and humidity levels?

The effect of increased airflow on an individual's thermal comfort was revealed. It involves working within operative temperatures between 24 and 30 degrees Celsius, with relative humidity between 40 and 60%, a work activity level between 1 and 1.4 MET, and clothing level between 0.5 and 0.6 MET. The air speeds required to achieve the right comfort level range between 0.23 and 1.5 m/s. Besides these factors, the type of airflow is also important, with a power spectrum closer to $\beta \approx 1.8$ rather than ≈ 0.60, and a turbulence intensity between 40% and 60%.

What is the effect of personal control on applications providing elevated airspeed?

For an application that offers increased airspeed and is personally adjustable, several elements are important. The intensity needs to be regulated with a fine-tune button allowing manual adjustment of the air output from the device, featuring a round dial of approximately 7 cm. The airflow must be very precise and able to be independently regulated and directed at the head and arms. Additionally, there should be an on/off button for people with a strong internal locus of control and an automatic function for those with a strong external locus of control. The primary control always lies with the end-user and not with central building management, which only has the authority to shut down the entire system. Communication from the device to the occupant should be in terms of warmer or cooler, not more or less wind. Thus, the effect is the focus, not the method. Additionally, communication to the user should first be conveyed through physical elements, then symbols, and finally text. All of this must be done without the device causing any noise disturbance or drafts felt by other occupants.

What are the advantages and disadvantages of various applications that enhance airflow to promote thermal comfort?

The pros and cons of systems that generate increased airspeed to improve thermal comfort primarily focus on specific domains. Some applications are highly performance-oriented, while others offer better control. It's important to find a good balance between the three areas of control, performance, and robustness to achieve effective implementation.

How do we provide an effective methodology for designing a breezemaker application in open-plan offices?

An effective methodology for a breezemaker device focuses on the areas of control, performance, and robustness, among which there is a certain hierarchy. This starts with dividing the factors into what must be implemented and what should be implemented. In the must-have group, a distinction is made between criteria and requirements, where the criteria control the requirements to arrive at an effective design.

How can we effectively integrate a breezemaker application in open-plan offices?

To effectively integrate a breezemaker application in open-plan offices, it is necessary to understand both the users' and the designers', investors', and maintenance personnel's perspectives and place these in the areas of control, performance, and robustness. This involves considering the experiences and expectations of users, as well as insights and expertise from experts. It is then important to clearly define the sub-functions of the system to systematically design and combine them into a coherent design that is continuously evaluated against the predetermined design criteria.

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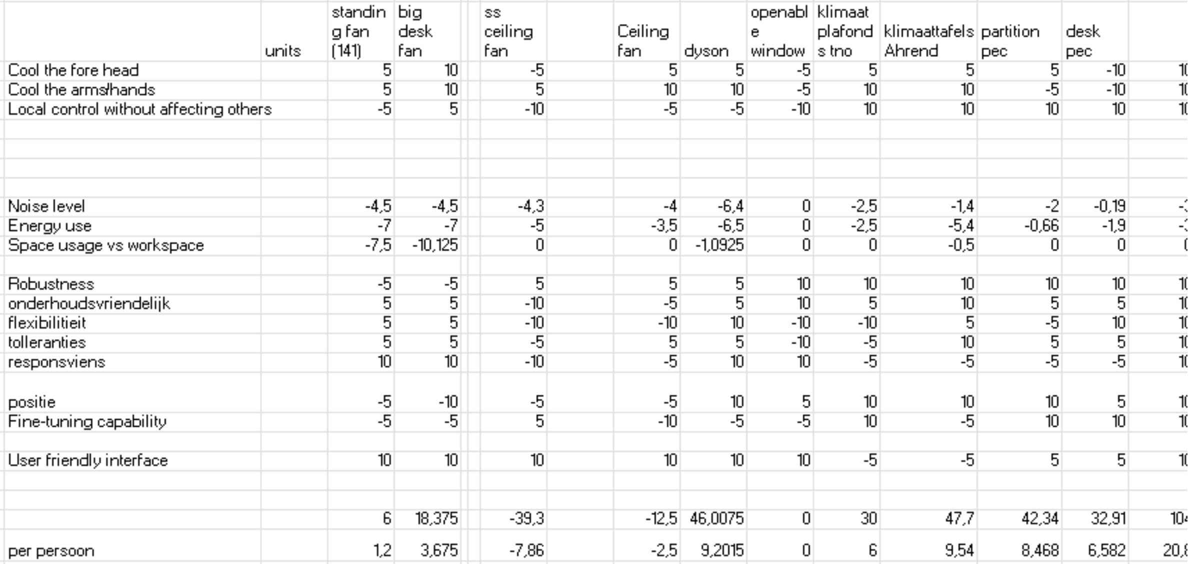
APPENDIX

Appendix

Appendix A



	units	standing fan (141)	big desk fan	ss ceiling fan		Ceiling fan	dyson	openable window	klimaat plafonds tno	klimaattafels Ahrend	partition pec	desk pec	
Cool the fore head		5	10	-5		5	5	-5	5	5	5	-10	1
Cool the arms/hands		5	10	5		10	10	-5	10	10	-5	-10	1
Local control without affecting others		-5	5	-10		-5	-5	-10	10	10	10	10	1
Noise level		-4,5	-4,5	-4,3		-4	-6,4	0	-2,5	-1,4	-2	-0,19	-
Energy use		-7	-7	-5		-3,5	-6,5	0	-2,5	-5,4	-0,66	-1,9	-
Space usage vs workspace		-7,5	-10,125	0		0	-1,0925	0	0	-0,5	0	0	
Robustness		-5	-5	5		5	5	10	10	10	10	10	1
onderhoudsvriendelijk		5	5	-10		-5	5	10	5	10	5	5	1
flexibilitieit		5	5	-10		-10	10	-10	-10	5	-5	10	1
tolleranties		5	5	-5		5	5	-10	-5	10	5	5	1
responsviens		10	10	-10		-5	10	10	-5	-5	-5	-5	1
positie		-5	-10	-5		-5	10	5	10	10	10	5	1
Fine-tuning capability		-5	-5	5		-10	-5	-5	10	-5	10	10	1
User friendly interface		10	10	10		10	10	10	-5	-5	5	5	1
		6	18,375	-39,3		-12,5	46,0075	0	30	47,7	42,34	32,91	10
per persoon		1,2	3,675	-7,86		-2,5	9,2015	0	6	9,54	8,468	6,582	20,

Appendix B: Interview questions

Opening questions:

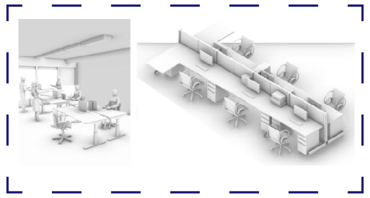
-Can you describe your current position and the associated tasks?
-Do you agree with the perception that many users in office buildings have no influence on their thermal comfort?

Visual stimulation:

Getty Images, 2018 MUTE, 2021

Ideation of different spaces

Personal situational experiences from the



More abstract environments

Primary questions:

Performance:

-On which parts of the body should the wind be directed?
-Where does that wind come from?
-Where is the application from which the wind comes located?
-What response do you want to receive?
-What aspects would you like to be able to influence?

Control:

-Where is the control located?
-How is it clear that the control belongs to the application?
-Is the control digital or analog?
-What is the response of the control?
-To what extent can you fine-tune?
-How easy is it to use?
-What is intuitive about the control?
-How is it clear that you have control?
-What is automatic about the system, and in what way do you, as an individual, want control?

Robustness:

-What kind of material would you like the device to be made of?
-What is the application attached to?
-How integrated is the device?
-When do you consider the product to be optimal?

Concluding questions:

-Is there anything else you would like to add on this topic or any further recommendations?
-What is your opinion on the yet-to-be-designed application?
-Is there anything else you would like to share?

Appendix C: Identified Design factors

Design Factors	Frequency									Interpretation and Description
	U	ME	IBP	IC	DE	FM	IA	IM	Total	
Airflow on arms, head, and feet	69	00	0	18	0	0	00	14	101	*Absolute user requirements appear to be hands and arms. However, people absolutely do not want lenses, glasses, or long hair on their heads, but they do want the rest. Additionally, a large portion indicates a desire to cool their feet. Cooling the neck and shoulders (backside) is interpreted more as a wish. It lies outside the scope of this research, but some people als find potential cooling in the chair attractive.*
Energy Efficiency	0	0	34	6	11	0	1	2	54	*Users do not mention energy consumption. However, installation and building physics experts frequently mention energy usage compared to other experts. There isn't really a specific number to give except that you should ensure it remains as low as possible.*
Airspeed	4	2	1	33	0	1	0	4	45	*The indoor climate specialist agrees with the research and emphasizes the importance of airflow speeds between 0 and 1 m/s. Users mainly express a preference for a breeze over a strong wind. They do not consider airspeed as a concept; it's something technical.*
Hinder: noise and draft felt by other occupants	9	2	3	10	2	0	2	0	34	*The first thing people mention under obstruction is noise pollution. Secondly, they often express not wanting to hinder others in the room with noise, or to receive wind that is not intended for them. Some correspondents also associate certain systems with a strange smell. If this occurs, they prefer not to use it and prefer to be too warm than the other way around.*
Flexibility of office floor plan	0	3	0	0	8	7	9	0	27	*Interior architects and maintenance personnel indicate that floor plans are often changed frequently. Therefore, building-bound solutions in this regard are often not preferred, as things are frequently shifted around. Flexibility should especially align with the table setup.*
Integration of device	4	3	1	0	0	4	10	0	22	*Interior architects, maintenance, management, and facility managers all indicate that the implementation should be based on standard building dimensions (300 mm standard) as the first integration possibility, integration by the user is mainly appreciated for being part of the environment/structure and not necessarily meaning that it has to be physically located somewhere. Both the manufacturer and users indicate that an application should not visually obstruct in the form of visual contact loss among other occupants in the room.*
Visual & Tangible feedback	21	0	0	0	0	0	0	0	21	*All users extensively share their experiences and expectations regarding responsiveness. Many examples and frustrations are discussed, whether the system performs as expected or not. Even situations where everything works satisfactorily, but the response is still deemed inadequate, are described. Response can be through the control, via sound, visual, or due to the short duration of the effect being felt. It's clear that it's a combination of elements. It's worth noting that none of the experts specifically indicated this.*
Digital interface	12	0	0	0	0	0	1	0	13	*Initially, few users choose a digital interface, but upon further questioning, they find it interesting, especially for flexible workspaces or as an additional option. A digital interface means using a mobile device but could also involve an employee card that ensures all settings are correct once the card is placed on it. Furthermore, they suggest that for those who enjoy creating interfaces that provide more explanations, more options are desirable, but not as the first step digitally.*
Physical interface	9	2	1	0	0	0	0	0	12	*Users prefer a physical interface over a digital one, often because they want to start immediately and have a strong distrust of digital or smart building systems.*
Sustainable material	3	0	0	0	0	2	2	2	9	*When asked about by users, interior architects, and others, everyone emphasizes the desire to see sustainable materials. Only the manufacturer points out that sustainable does not necessarily mean the lowest CO2 emissions at that moment. As an example, he uses a tabletop. It can be separated from the rest of the table, the finish can be removed, and a new finish applied, while the base and the majority of the tabletop remain the same.*
Horizontally and vertically directed airflow	0	0	0	7	0	0	0	0	7	*All users initially prefer horizontal ventilation, with the option for vertical being possible only for the shoulder and neck. The indoor climate specialist also prefers horizontal ventilation. Another important element that must be taken into account is that the horizontal airflow should not blow away papers.*
Intensity of the airflow	6	0	0	1	0	0	0	0	7	*Intensity is a term used frequently by users, who often find the wind too intense and unpleasant. The indoor climate specialist concurs, stating that for large body areas, it's more important to ventilate the same cubic meter of air but distributed over a larger surface area is preferred over selectively flowing air to specific body parts.*
Materials that stay cool during warmer temperatures	5	0	0	0	1	0	1	0	7	*The ergonomist and interior architects primarily aim for natural materials for various reasons, including sustainability, but also because they remain relatively stable in both warm and cold environments. Think of materials like leather and wood.*
Air quality	2	0	0	2	0	0	1	0	5	*Many people also associate warm temperatures with stuffy rooms/poor indoor air quality. They often reference that an open window symbolizes clean air for them. Good air quality is important, but it only applies in this application when it also involves fresh air supply. In the case of recirculation, the air quality must already be good, otherwise HEPA filters can be installed, for example.*
Maintenance-friendly	0	1	0		0	3	0	2	5	*For maintenance and manufacturers, it's important that the product is maintenance-friendly. This relates to both the materials used and the finishing. For instance, if it's on a work surface, it's preferable to have no seams where crumbs/dust can accumulate, as this isn't easily cleaned. Additionally, it is important that fans do not get dirty quickly to prevent noise pollution, therefore they recommend using a filter.*
Airflow adjustable per body part	4	0	0	0	0	0	0	0	4	*Many users express the importance of being able to control each body part separately. Even within the head area, there should be sufficient options to provide wind to specific parts or not. It's noteworthy that the head is the most precise, followed by the hands and arms, then the chest, and finally the feet. It could almost be argued that feet may even have a static position since they may not affect other parts. One could argue that there*

Design Factors	Frequency									Interpretation and Description
	U	ME	IBP	IC	DE	FM	IA	IM	Total	
										should be a 180-degree freedom of movement so that there is complete freedom in what you want to cool or not.
Automatic function	3	0	0	0	0	0	1	0	4	*Users are open to this product, but they also have a strong opinion that it should simply be "regulated." Some correspondents prefer, just like in a car, an automatic button that adjusts it for you and where necessary, you can adjust it yourself. They prefer having to readjust it from one setting to another rather than from nothing to something.*
Central adjustable option	0	1	2	0	0	0	0	0	3	*Closely related to primary control, suggestions from building physics, maintenance, and manufacturing emphasize having some form of central regulation. This could range from something as simple as tapping into an existing power group that centrally turns on/off to a complex function with presence sensors connected to central facilities.*
Presence sensors	1	0	1	0	0	0	1	0	3	*Presence sensors are particularly encouraged by maintenance and building physics because this can save a tremendous amount of energy. Many users have had negative experiences with sensors, but presence sensors such as light sensors are well developed and often perform very well. However, they should not be relied upon as the primary on/off mechanism.*
Disassemblable	0	1	0	0	0	0	2	0	3	*From the users' perspective, as well as maintenance, the design should initially not be part of another function, both for complexity and sustainability reasons. On the other hand, the manufacturer argues that if it's part of a tabletop, ensure it stays that way, as if you want something else later, you only need to replace that tabletop.*
Position of the device and control point	0	0	0	0	0	0	1	0	1	*They don't find the distance from which the wind comes very significant, but they're more concerned about the accessibility of the control and its connection to the device. They mainly explain that if they could see it, it would be used earlier than if, for example, it hangs above your head. The ergonomist, but especially users, indicate that the 3rd ergonomic zone, which cannot be reached from a normal sitting position, would be the ideal location to place the application when the desk surface is taken as a reference point. They also mention that control should be possible from the normal position but not obstructive, meaning it should be in the 2nd ergonomic position.*
Complexity of the system	0	1	0	0	0	0	0		1	*Maintenance, in particular, is concerned about excessive complexity. They often see failures in many new systems. They emphasize strongly that the foundation must be truly simple. While there can be plenty of expansion options, there should be something with low complexity to choose from the outset. Complexity can always be increased later.*
On/off function	7	0	0	0	0	0	0	0	0	*Many users find it important to have a simple on/off button on the system that can be operated independently of other settings. They, along with other experts, indicate that the primary control should also lie with the end user. This primary control can, for example, be found in these buttons. Maintenance agrees that this is possible but also suggests considering an additional central option.*

U = Users **|** **ME** = Maintenance Engineers **|** **IBP** = Installations & Building Physics Expert **|** **IC** = Indoor Climate Expert
DE = Design Ergonomics Expert **|** **FM** = Facility Manager **|** **IA** = Interior Architect **|** **IM** = Interior Manufacturer

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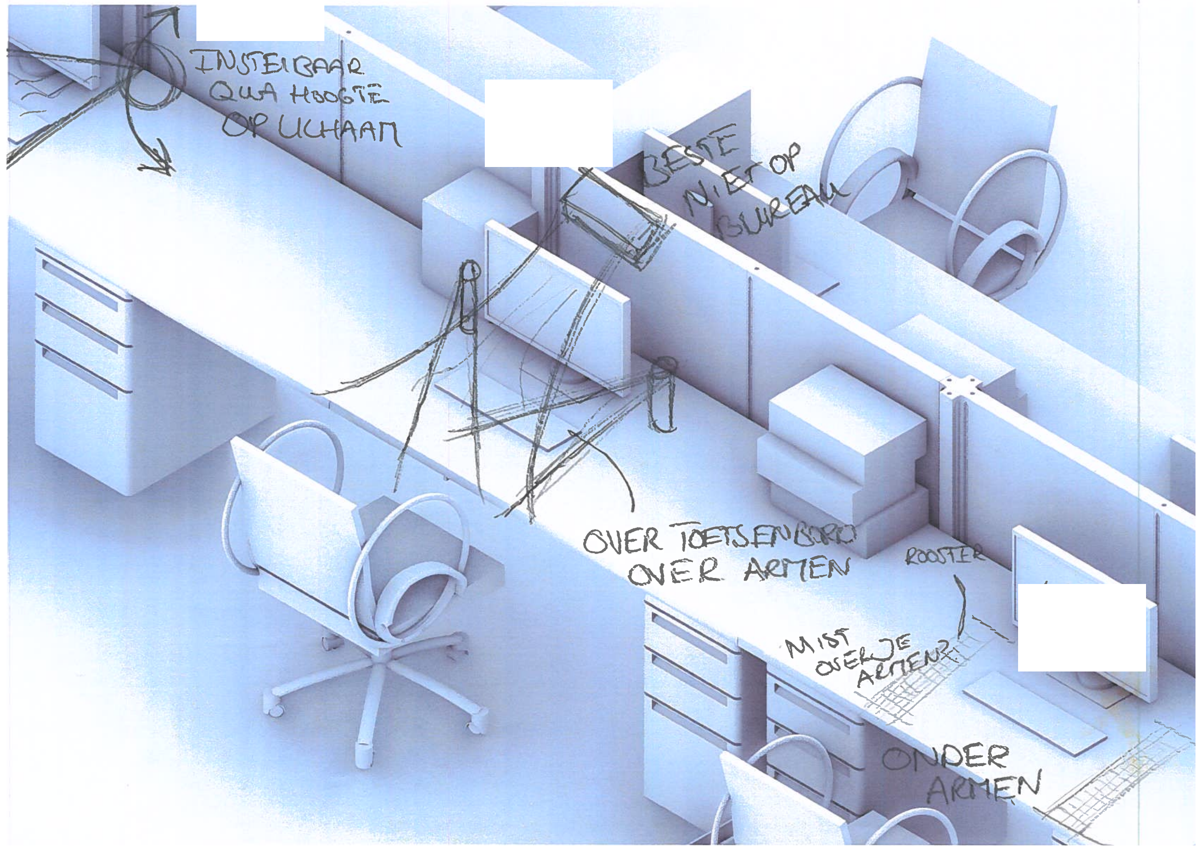
Design Factors	Frequency									Interpretation and Description
	U	ME	IBP	IC	DE	FM	IA	IM	Total	
Fine-tuning function	1	0	0	0	0	0	0	0	0	*Fine-tuning is not a major concern for users, except that they often reference car controls, which they find convenient. They also mention preferring a continuous control recognized by points, rather than being dimensionless. When given the choice between 0-1, 0-10, or 0-100, opinions were divided, but a slight majority favored 0-10. The indoor climate expert particularly emphasized fine-tuning between 0 and 1/ ms, stating that users should be able to regulate it well, not just providing options like 2 m/s.*
Tolerances of the device	0	0	0	0	0	0	0	0	0	*The tolerances of this adjustment primarily concern where the application is attached. Experts and users find it important that it should also be applicable to many existing situations. So, whether it is attached to ceilings, tables, floors, walls, etc., adhere to those characteristics, ensuring that the attachment is sturdy and perhaps overdimensioned because in practice, it is often observed that while the design itself is robust enough, the connection is often the weakest point.*
Character use	-	-	-	-	-	-	-	-	-	*Users mentioned that future characters should not resemble characters/buttons found in other climate systems unless it's ventilation-focused. They specifically reference auto ventilation symbols but exclude traditional thermostat buttons. From the drawings and discussions, it becomes apparent that both symbols and letters should be used, but primary communication should occur through symbols, with letters being secondary.*

U = Users **|** **ME** = Maintenance Engineers **|** **IBP** = Installations & Building Physics Expert **|** **IC** = Indoor Climate Expert
DE = Design Ergonomics Expert **|** **FM** = Facility Manager **|** **IA** = Interior Architect **|** **IM** = Interior Manufacturer

Appendix D: Drawings from geinterviewden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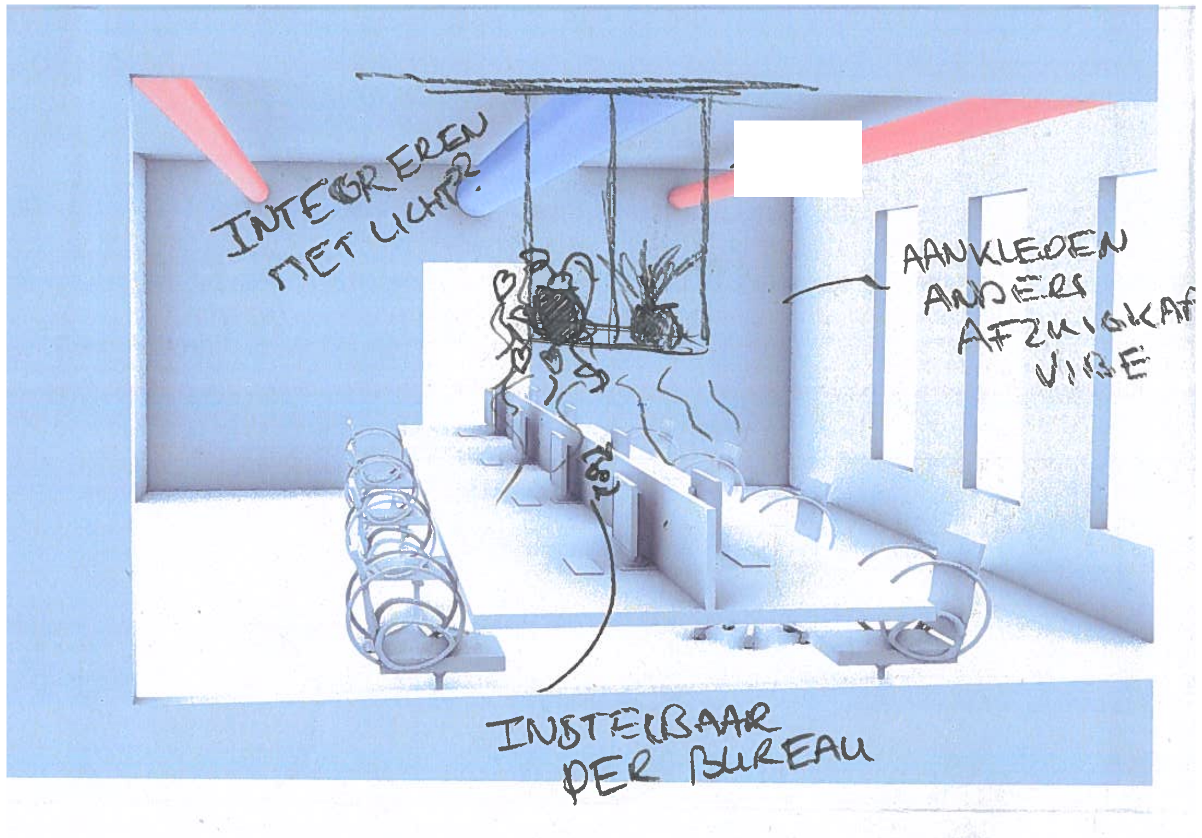
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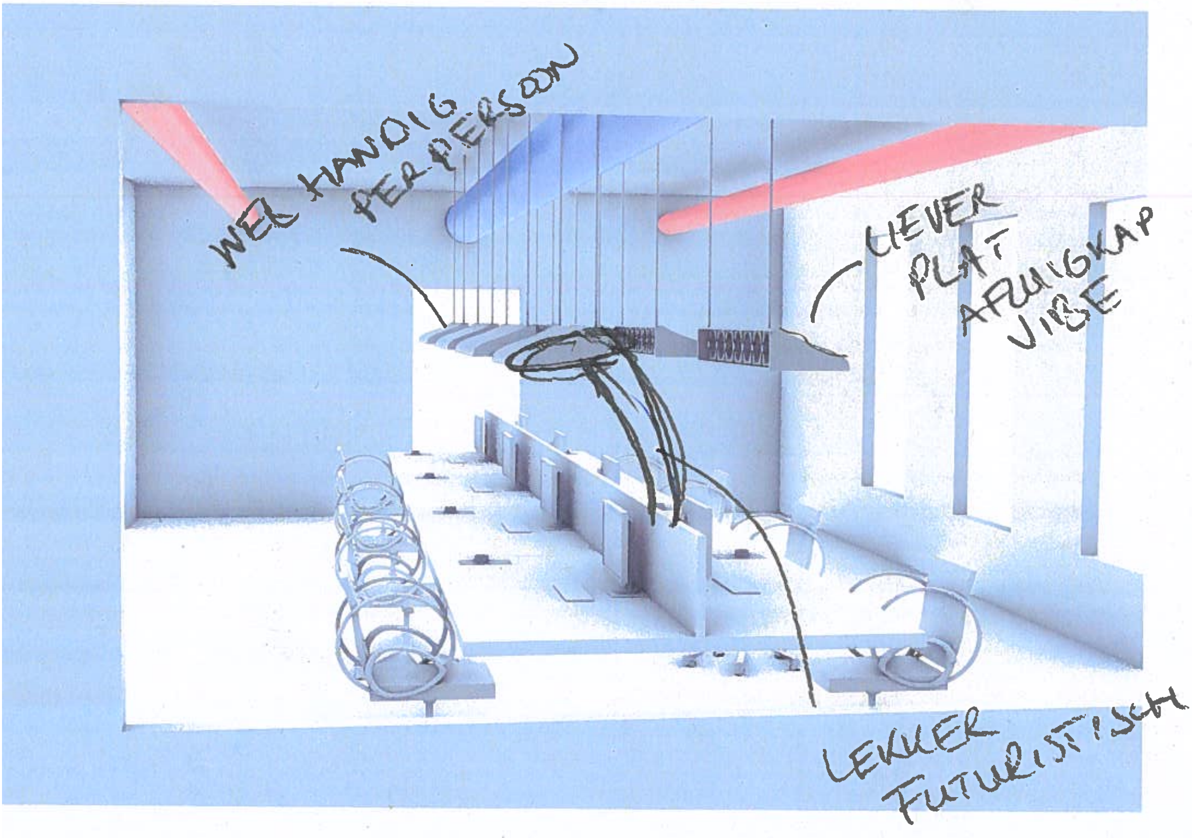
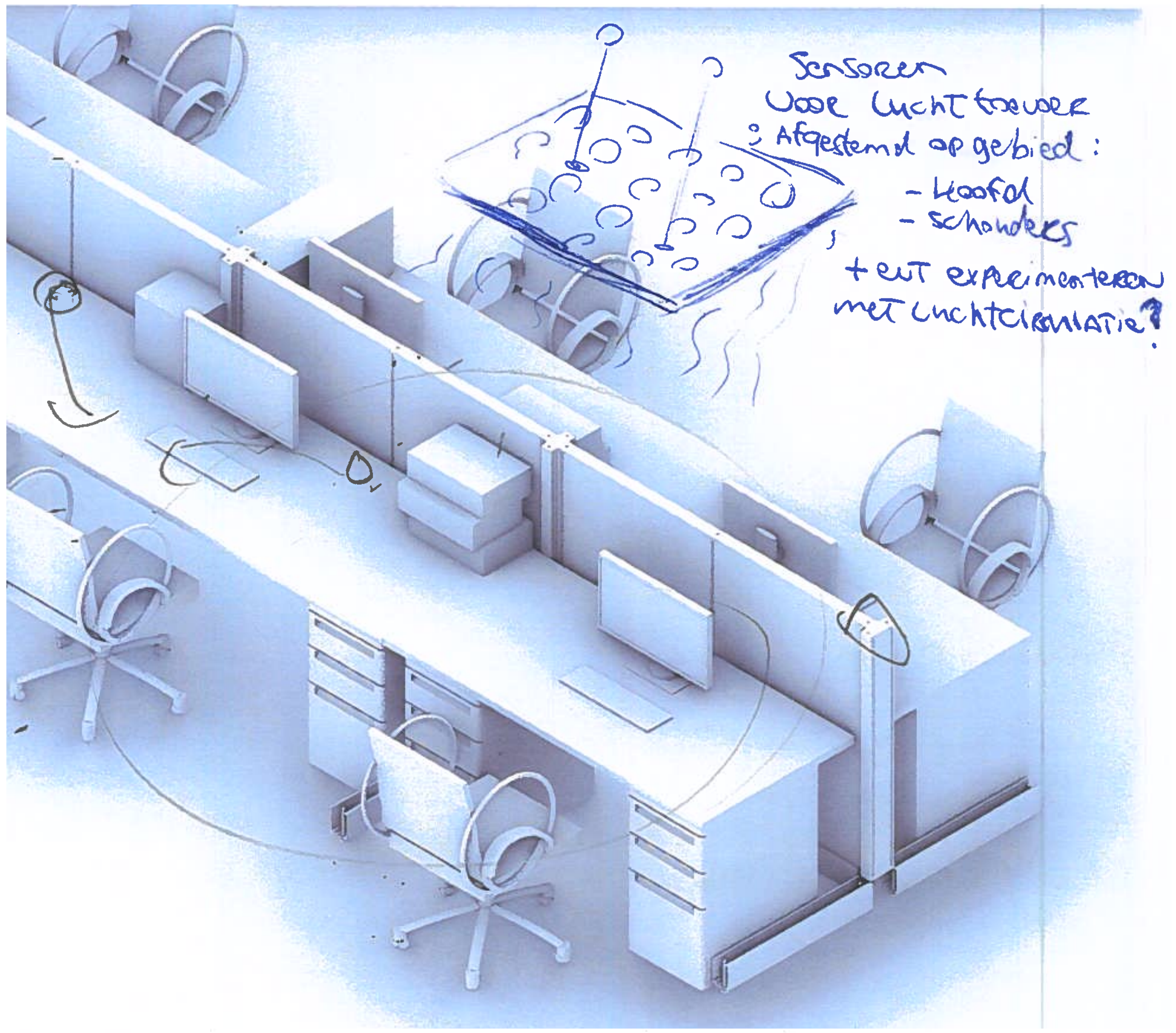
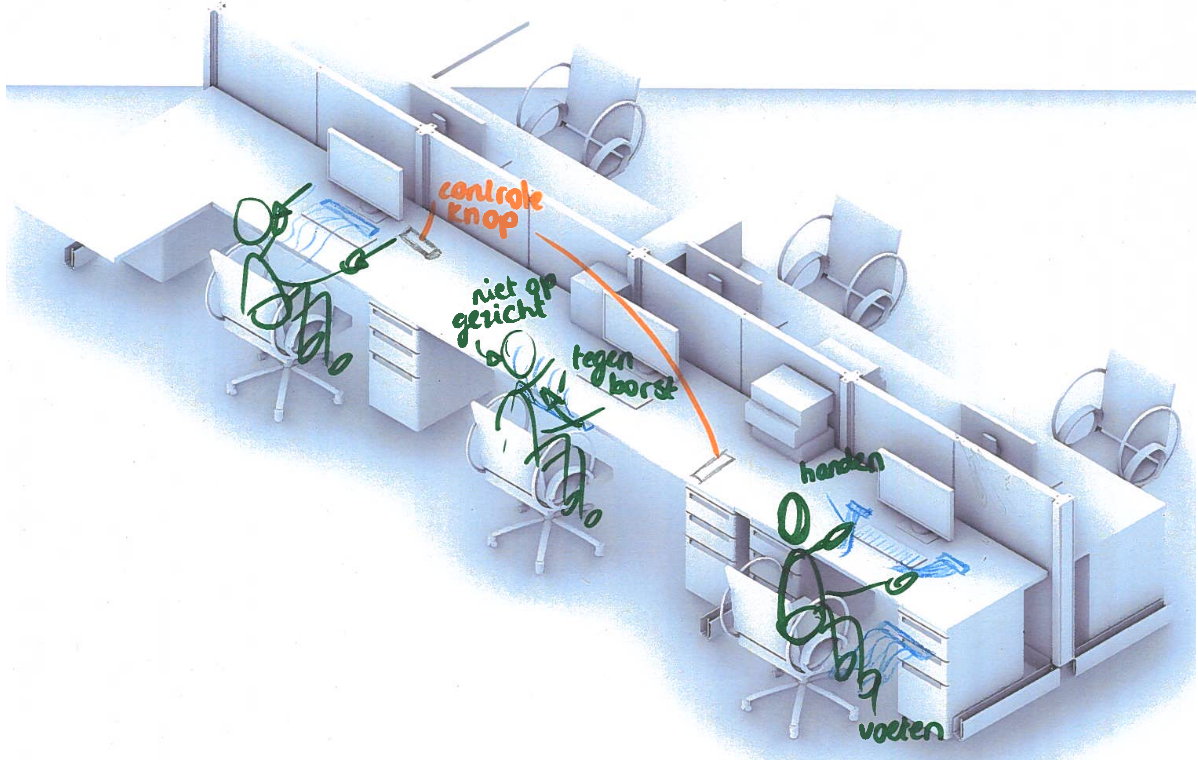



Sensoren
Voor luchttoevoer
Afgestemd op gebied:
- hoofd
- schouders
+ evt experimenteren
met luchtcirculatie?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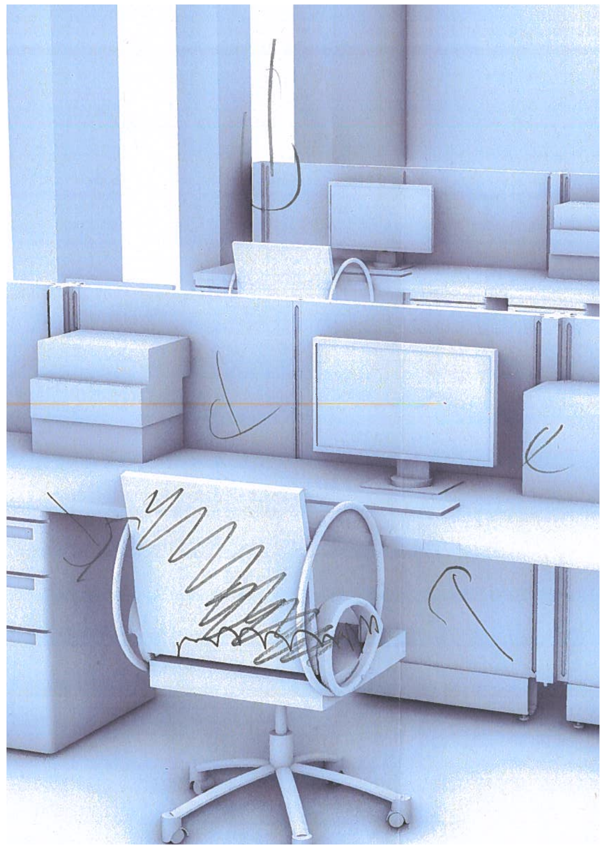

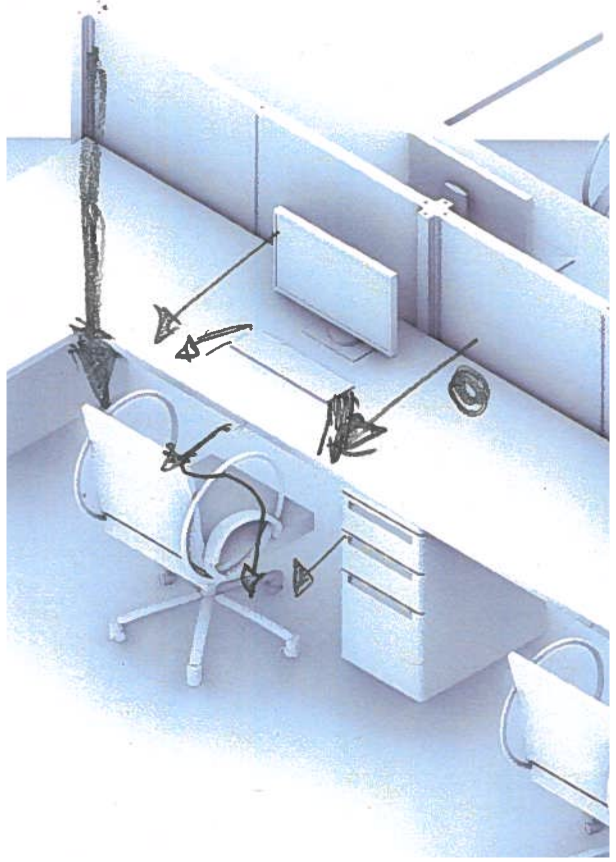

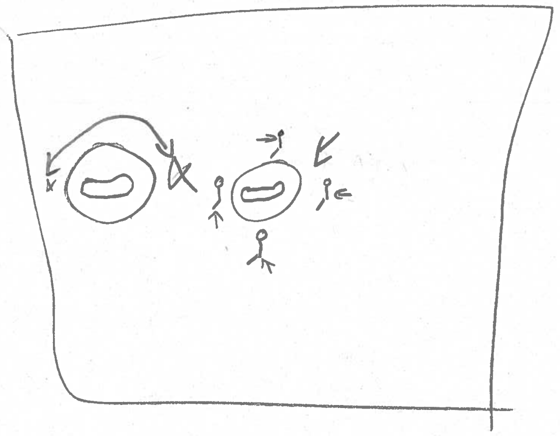

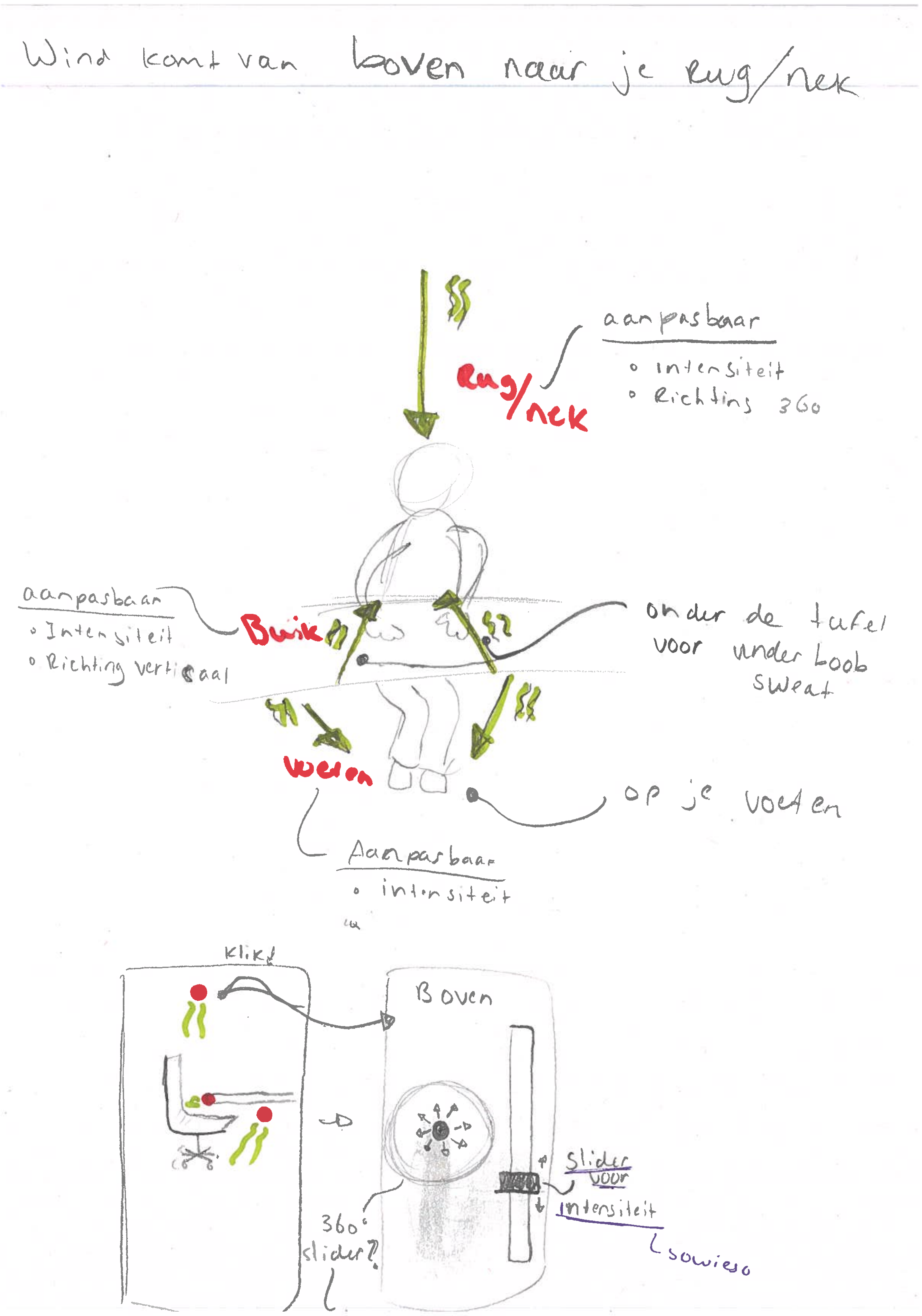
Wind komt van boven naar je rug/nek
Rug/nek
aanpasbaar
∘ intensiteit
∘ Richting 360
aanpasbaar
∘ Intensiteit
∘ Richting verticaal
Buik
onder de tafel
voor under boob sweat
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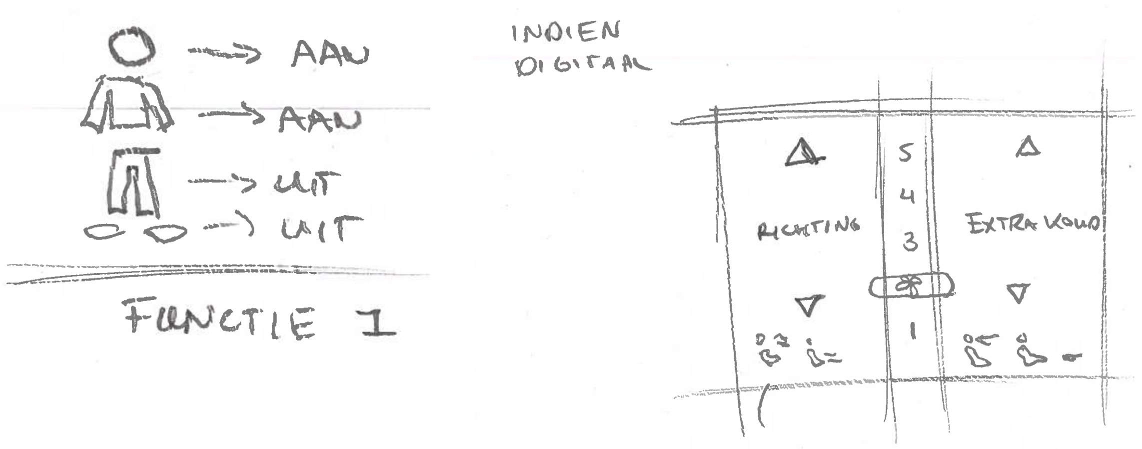
op je voeten
Aanpasbaar
∘ intensiteit
Klik!
Boven
Slider voor intensiteit
sowieso
360° slider?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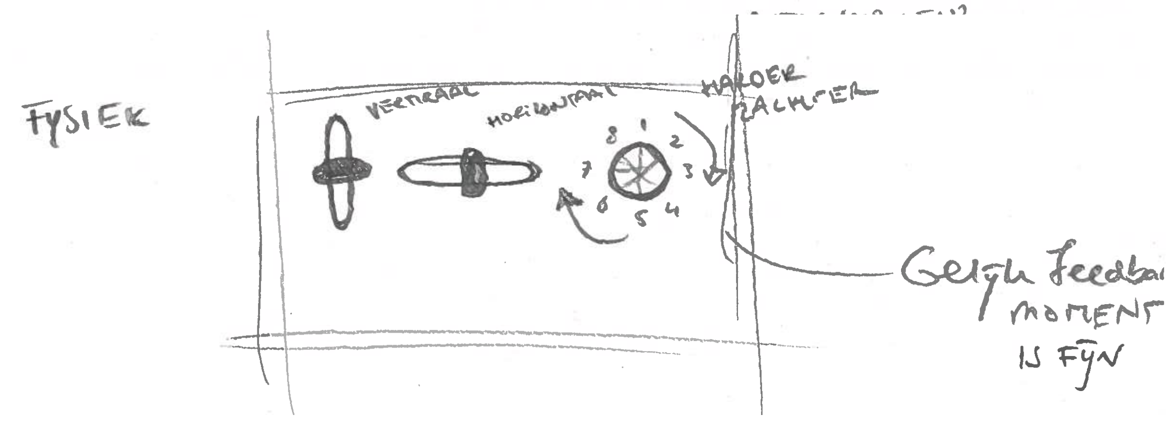
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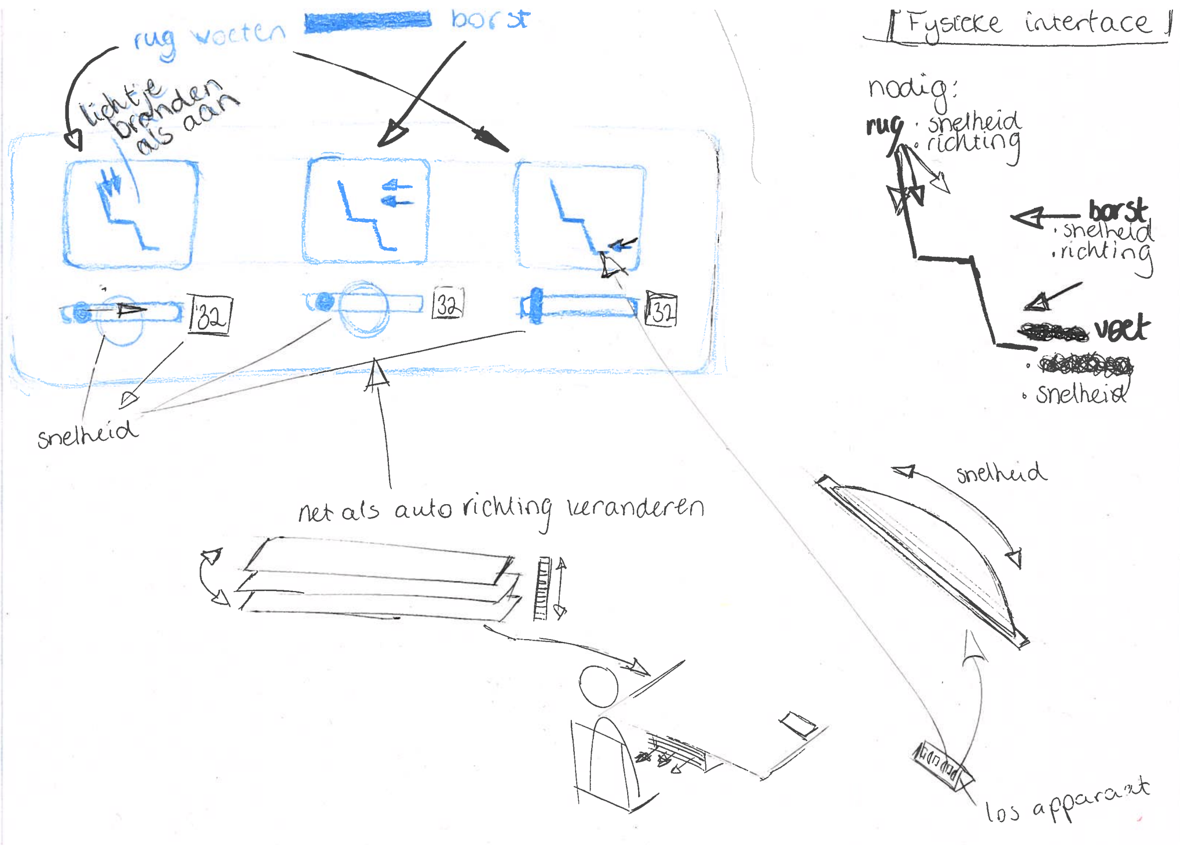
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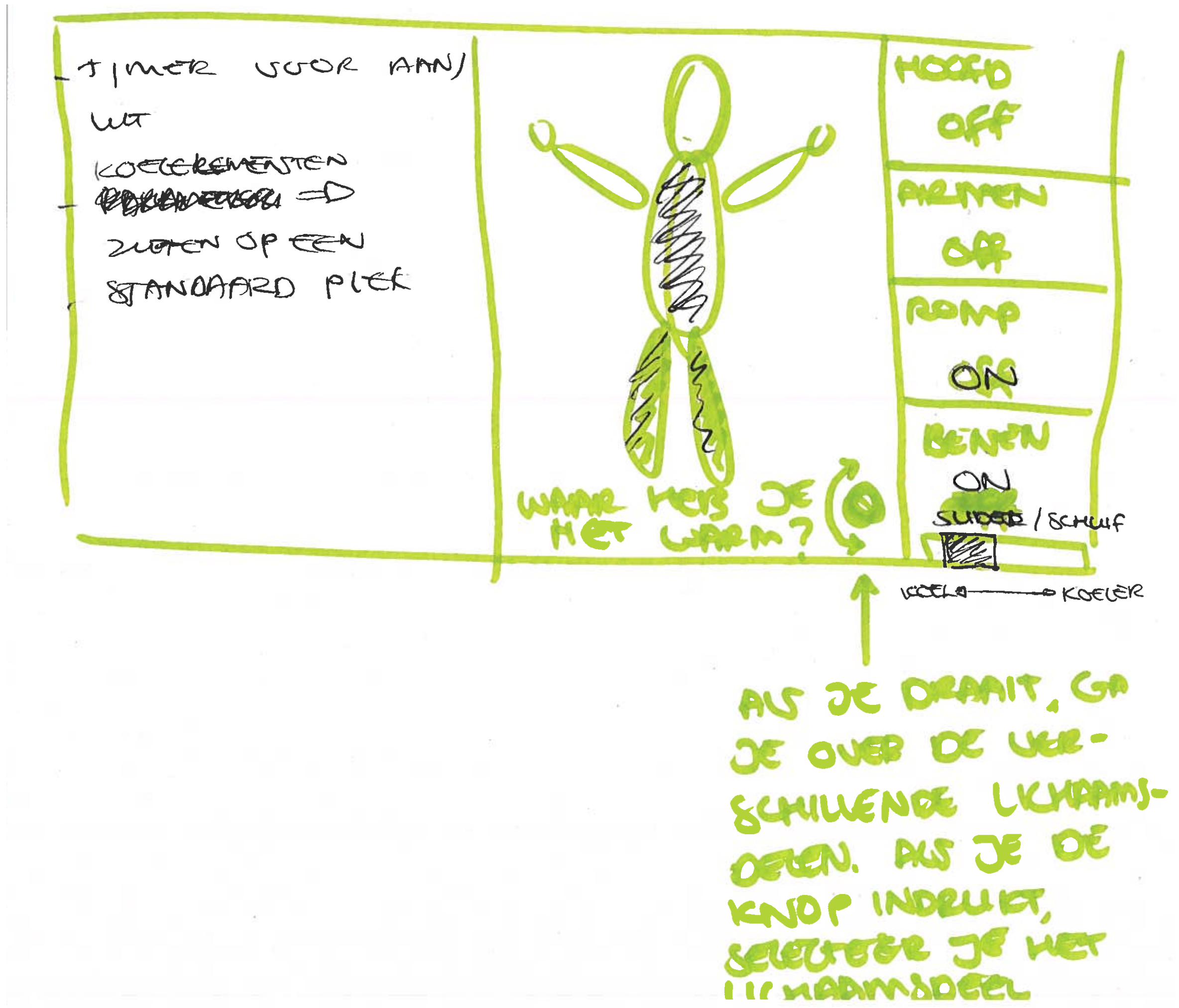
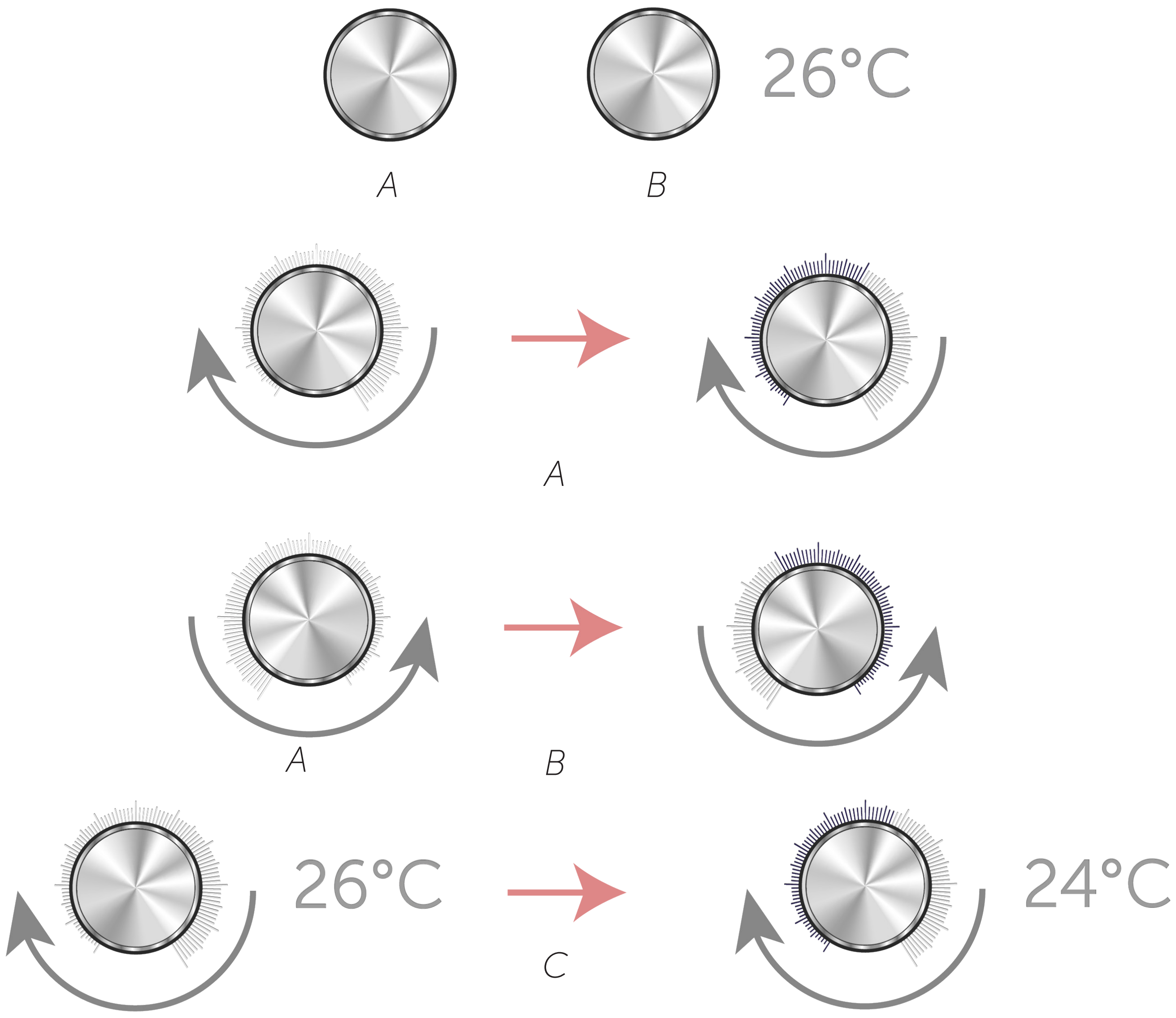


Appendix E

	Performance	Control	Robustness
Must	*- Jointly no more than 40 dB* *- No disturbing noises compared to the base environment* *- No noticeable airflow for other users* *- Airspeed from 0 to 1.5 m/s* *- Airflow spread over the largest possible area* *- Device > 3 ergonomic zones* *- Controls in the 2nd or beginning of the 3rd ergonomic zone* *- Symmetric distribution* *- Top and middle cooled* *- Air quality is at least the same quality as the surrounding environment* *- Energy-efficient as possible*	*- Visual feedback* *- Tangible feedback* *- Each body part operable independently* *- Direction changeable per body part* *- Equal intensity throughout the body* *- Fine-tuning between 0 and 1.5 degrees Celsius* *- Scale usage from 0 to 10 or temperature* *- On/Off button* *- Automatic function button based on operating temperature* *- Primary interface is physical* *- Hierarchy of control is button, symbol, and then letters*	*- Visually integrated into office environment* *- Grid size 300 mm or related to furniture size* *- Utilizing clear layers* *- Not hindering flexibility* *- Available in multiple colors* *- Basic maintenance should be possible by a non-expert*
Should	*- Air circulation around the feet* *- (HEPA) filter when air quality cannot be guaranteed* *- Filter for maintenance of fan*	*- Airflow as feedback/response* *- Communication focuses on warm and cold, not on more or less wind* *- Digital interface with memory functions or customizable settings* *- Playfulness in design* *- Presence sensors* *- Building central On/Off switch for the system*	*- Minimal exposure of mechanics* *- No dirt between connection environment and device.* *- Furniture-oriented* *- Demountable* *- High thermal conductivity* *- Minimizing radiation output* *- Preference for textured surfaces over completely smooth ones* *- Integration with an existing function* *- Tolerances for user freedom* *- Utilization of sustainable materials*

Appendix F

1.



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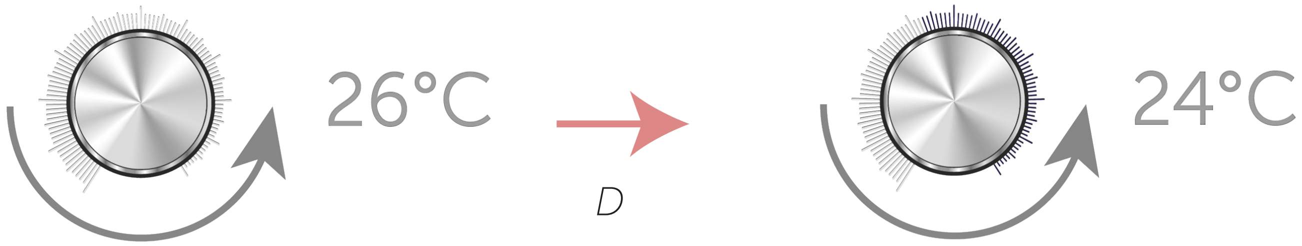

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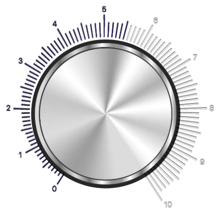
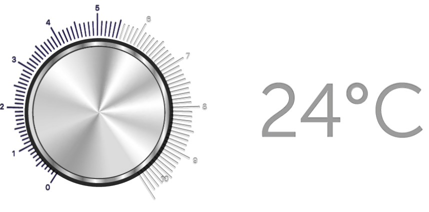


4.



5.