PERSONAL AIR FILTER

A purpose-designed air purifier to reduce the spread of airborne transmissive diseases in offices

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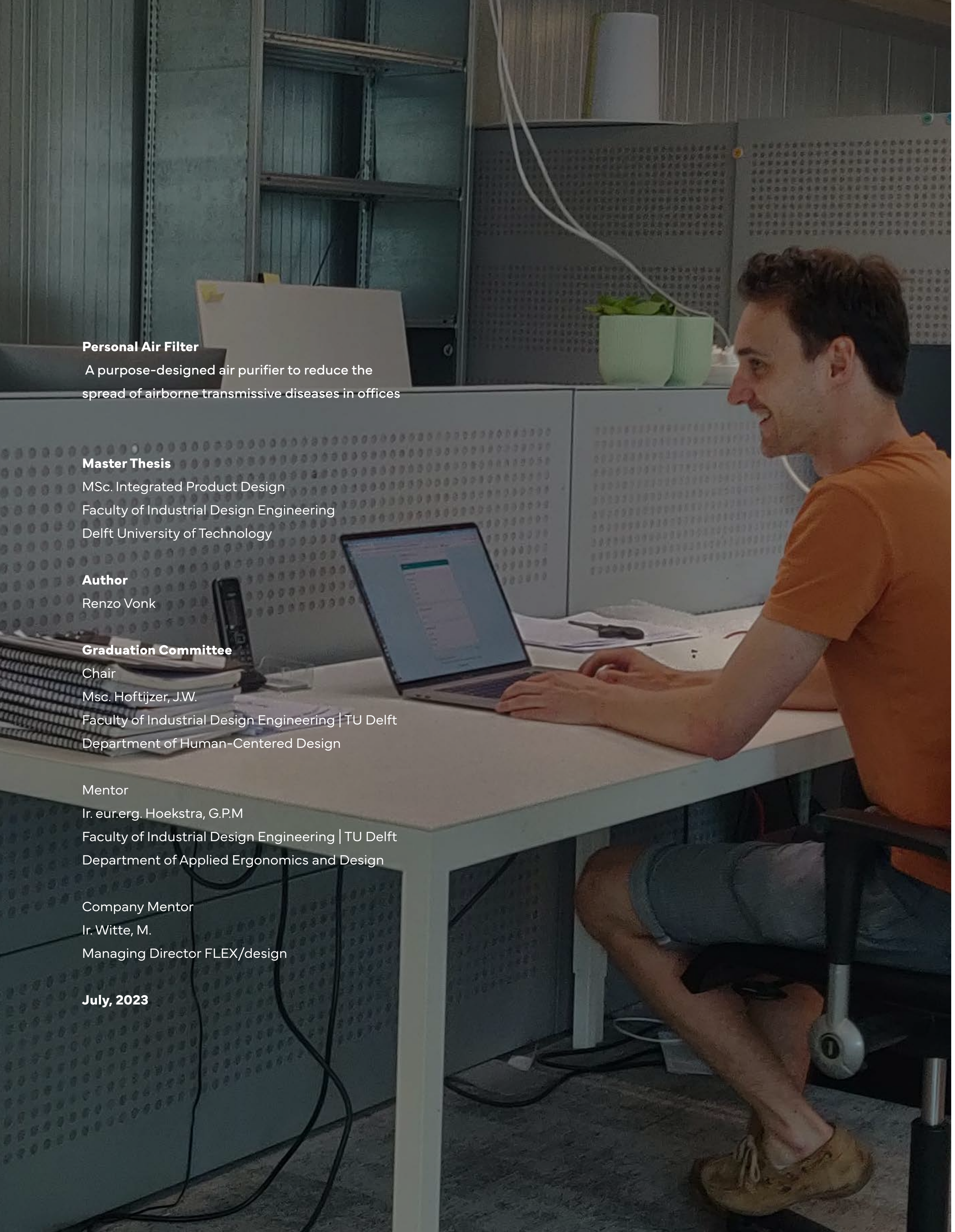

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Master Thesis
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Preface

I would like start by expressing my appreciation for all of those who supported and guided on a professional and personal level throughout the journey of my master thesis.

First of all, I want to take a moment to thank my chair and mentor, Jan Willem Hoftijzer and Gonny Hoekstra for their time and efforts in helping me along the way. You went beyond supervising me by motivating me in all the aspects of this project. I appreciate your compassionate guidance and your encouragement to take a break when needed. Thank you for all the interesting discussions, expertise, and helping me to broaden my view and prioritise when required.

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Furthermore, I would not have been able to do this project without the knowledge from many experts involved throughout the process. I'd like to mention some people who were instrumental to shaping the project to what it is. First and foremost, Ard van Bergeijk and Barry Dallinga from Euromate, you provided relevant feedback and expertise where needed. Thank you for your time and the invaluable meetings we had. Also, a big thank you to Carolien Sloot and Annalies Nijlant from TopInterieurOntwerpers for your interest and contribution about office interior design. Furthermore, Gijsbert van Marrewijk, your help with evaluating the CFD analysis and tips to improve the design. A further thank you to all other experts who contributed to the project.

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SUMMARY

The COVID-19 pandemic has highlighted the importance of indoor air quality in preventing the spread of airborne transmissive diseases. Offices are some of the largest hotspots for disease transmission. To address this issue, a joint venture between FLEX/design and Euromate, called 'X-Lair,' aims to design an air purifier specifically targeting the reduction of airborne disease transmission.

This project focuses on developing an air purifier solution that not only effectively reduces the spread of airborne diseases but also considers user experience and implementation in office environments. While primarily designed for placement above desks, the proposed solution has the potential to be applicable in various contexts.

Extensive literature research, user tests, empirical studies, interviews, and mind-mapping techniques have been employed to explore the research domain, identify design drivers, and establish a list of requirements. An iterative design approach, including tests with smoke and computational fluid dynamic analysis, have guided key design decisions. Additional tools such as Midjourney and virtual reality have facilitated the elaboration and visualization of ideas in their intended environment.

The final design proposal of the Personal Air Filter features a suspended configuration above desks, providing a large capture area to effectively filter the user's breath. Plume propagation is considered by locating the air intake at the edge of the hood. An integrated lamp ensures comfortable ambient lighting, enhancing the device's aesthetic appeal in office settings and improving employee well-being. A user interface, including a smartphone application, allows for convenient control of ventilation speed and lighting intensity. Smart features like the 'smart mode' enable autonomous operation, while interconnectivity between multiple devices enhances overall effectiveness and reduces noise.

A functional prototype was developed to validate the device's efficacy and user experience. Smoke tests demonstrated the Personal Air Filter's effective smoke capture at both 100 and 200 m3/h, indicating the potential for downsizing the device without compromising its performance. Special attention should be paid, however, to ensure that the Personal Air Filter operates at an acceptable noise level below 45 dB, taking into consideration the need for a quiet and comfortable office environment. Furthermore, user tests emphasized the need for a smartphone application and adjustable height for the Personal Air Filter.

In summary, the design of the Personal Air Filter represents a significant advancement in improving indoor air quality and promoting the well-being of office employees. The Personal Air Filter has the potential to become a unique and effective solution for mitigating the spread of airborne transmissive diseases.

CHAPTER ONE

INTRODUCTION

This chapter introduces the problem the graduation project focuses on. A background on the origin of the project is given for a better understanding of the current knowledge and the task at hand. The project goal, relevant research questions, and scope of the project as well as the design process and methodology to achieve these goals are defined.

1.1 – Problem Introduction

In December 2019 a new variant of the Severe Acute Respiratory Syndrome (SARS) virus, SARS-Cov-2 (the virus that causes COVID-19) emerged in Wuhan, China. Within 3 months the virus had spread globally and was declared a pandemic on the 11th of March 2020 by the World Health Organisation. From 2020 to 2022 the world followed by imposing lockdowns, mandatory quarantines, social distancing, wearing facemasks, and organizational measures of remote working to prevent further spread. Today, the virus reaches an endemic phase as governments are easing restrictions allowing people to work in the office again. Nonetheless, with our knowledge today, employees still face large risks in contracting SARS-Cov-2 and other airborne transmissive diseases.

At the start of the Coronavirus pandemic, SARS-CoV-2 and other airborne transmissive diseases were thought to be spread primarily by large respiratory droplets and contaminated surfaces (fomites) (Kavanagh, 2022). Today aerosols[1] which can remain suspended in the air for long durations of time, are seen as the main route of transmission (REHVA, 2020a). For example, in a call centre in South Korea (seen in figure 1), 94 of 216 (44%) employees on the same floor contracted the virus (Park et al., 2020). A number of other outbreaks in indoor spaces, such as restaurants, churches, shopping centres, cruise ships, and more, showed that airborne transmission by aerosols is prevalent in poorly ventilated environments (Leclerc et al., 2020). Current research suggests a paradigm shift in our knowledge about airborne transmission of viruses and how improved ventilation can reduce the risk of virus transmission.

[1]
Aerosols are particles less than 50 micrometers in diameter. They can stay airborne for an extended period of time before settling on a surface or landing on a nearby person.

Figure 1
The floor plan of the 11th floor of building X, the site of a coronavirus outbreak in Seoul. The blue indicates the desks of people with confirmed cases (Park et al., 2020).

Ventilation is the process of introducing fresh outdoor air in a building through natural or mechanical methods (ISO, 2017). Before the Coronavirus pandemic, office ventilation standards were written to limit odors and dust, but not to control viruses (ASHRAE, 2022). With current knowledge about transmission through aerosols, we know that many offices today do not withstand recommended ventilation precautions (Morawska et al., 2020). Figure 2 shows how aerosols can spread through a room in a matter of minutes (HOLT Architects, 2020). The number of air changes per hour (ACH) can be used to give an indication of the ventilation rate. Most offices today have systems in place that produce 1 to 2 ACH whereas 5 ACH is recommended to curb the spread of airborne viruses (ASHRAE, 2022).

Many ventilation systems are designed for filters that are intended to remove larger particles and are not effective at removing small, sub micrometre or micrometre size particles (Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size, 2017).

Air filters can be used to purify air in a local area without the need of adjusting infrastructure, which can be costly. However if used improperly it can unintendedly mix 'dirty' stagnated air into the otherwise potentially clean breathing zone of the occupant (Public Health Ontario, 2022). Therefore, according to Morawska et al., air filters need to be purposely designed to control risk of airborne infection (2020). Removing the virus close to the source is the most effective strategy according to Bluyssen et al. (2021).

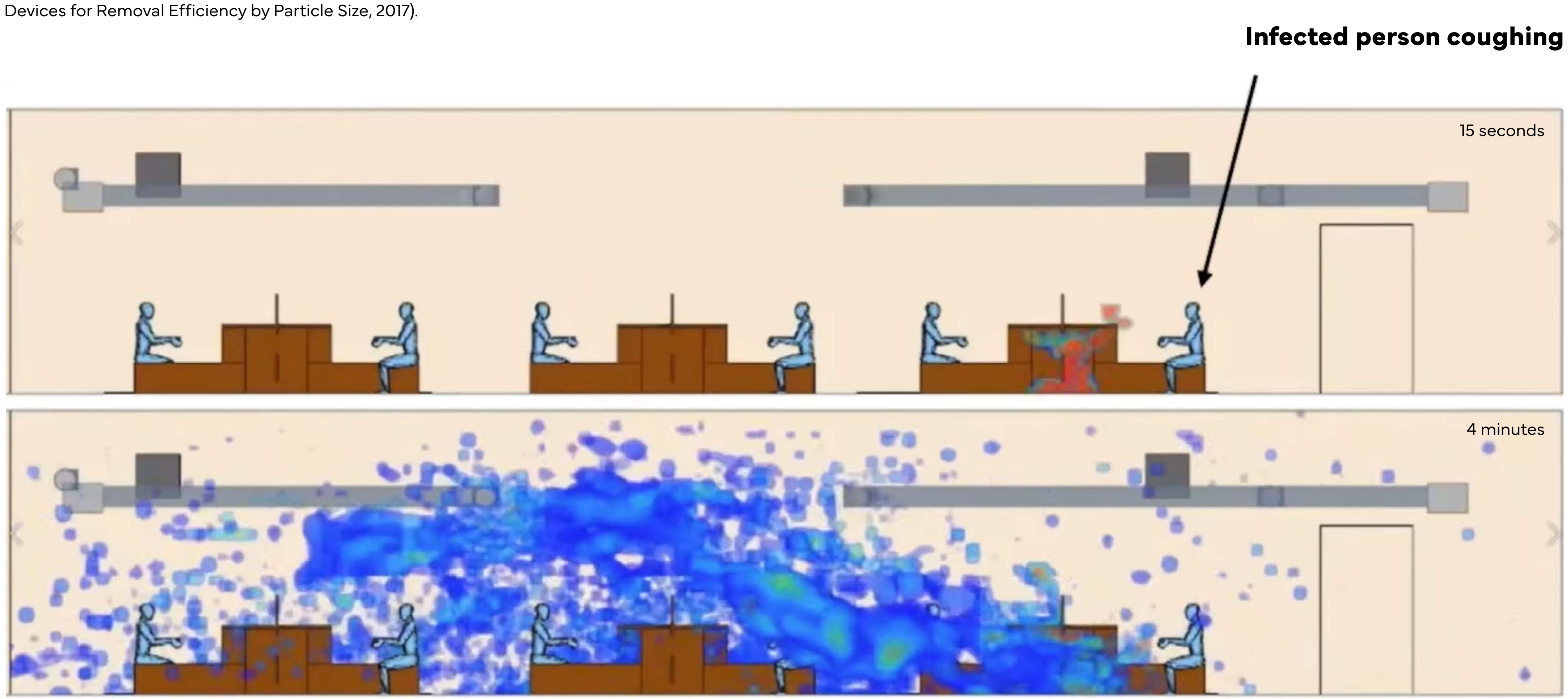


Figure 2

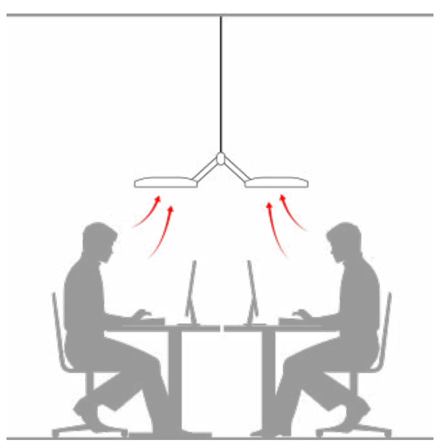
Simulation of infected person coughing in office environment at 15s and 4 minutes (HOLT Architects, 2020)

1.2 - Project Goal

A purpose-designed air filter to curb the spread of diseases for offices currently does not exist. Euromate and FLEX/design see this opportunity and have set up the joint venture 'X-Lair' to combat spreading of SARS-CoV-2 and other airborne transmissive diseases in office environments. This graduation project proposes the design of a Personal[2] Air Filter that reduces the risk of transmission of airborne transmissive diseases, enabling employees to work safely from the office.

Euromate is a specialist in cleaning indoor air for 45 years, such as reducing pollution from viruses, bacteria, fine particles, and odors. FLEX/design is one of the leading industrial design agencies in the Netherlands that develops a wide range of consumer products, smart products and experiences. In 2020 an initial product concept of the Personal Air Filter was made with the idea to create an air purifier for desk spaces that extracts and filters the air people breathe (figure 3). Though the design promised to be effective in filtering aerosols, it was unsuccessful in gaining the interest of investors for further product development.

[2]
A 'personal' air filter aims to capture an individuals breath and purify it so that no contaminants can spread further into the environment.



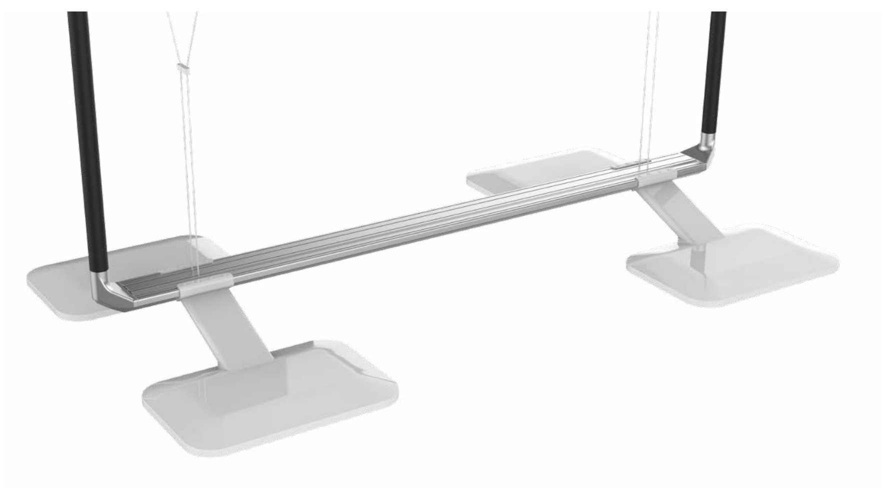


Figure 3
FLEX/design personal air filter concept suspended from the ceiling. Source: FLEX/design

The prototype and Computational Fluid Dynamic[3] (CFD) models indicated that the product extraced air effectively (figure 4 & 5). The 'suction hood' was in close proximity to the user and considered the propagation of air the user breathes. Working at the desk however proved to be "noisy, intrusive, and difficult to implement" (personal communication FLEX/design employee, 2022). The fans used in the extraction hoods were the quietest fans available, but still produced too much noise for concentrated work. Furthermore, the presence of the design above the users was undesirable as it may give a constant reminder of the risk of getting sick. Subsequently, a new improved design is necessary.

[3]
CFD uses numerical analysis and data structures to analyze, predict, and solve problems that involve fluid flows such as air.

Figure 4
FLEX/design prototype of the Personal Air Filter for validation.

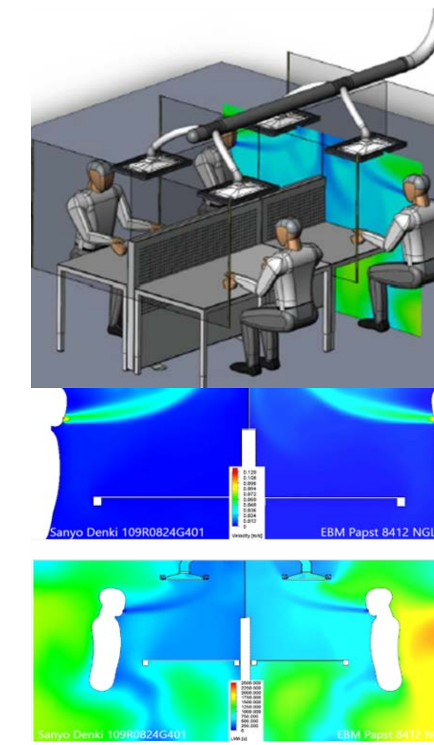


Figure 5
Voxdale CFD analysis for air velocity and air refreshment rate.

1.3 - Design Goal

The aim of the graduation project is to analyze and rethink the problem to come with an integrative solution that is more feasible and desirable. The goal is to design and develop a Personal Air Filter proven to be both effective in filtering aerosols as well as desirable to implement and use by the user. Personal Air Filter should optimize the trade-off between product use and performance. It must also work within the existing context, such as working well together with existing ventilation systems and being non-intrusive to implement in offices.

The project goal is summarized in the design vision:

"The trade-off between user experience and product performance should be optimized to create a feasible and desirable device.

The Personal Air Filter must work with existing ventilation systems and should be non-intrusive to implement in the office, ultimately improving air quality, reducing pollen, and viruses"

1.3.1 - Research Objectives

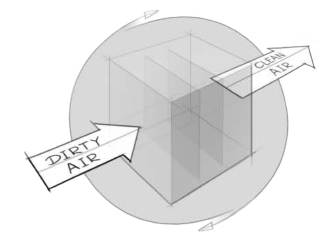
In order to find effective solutions for a Personal Air Filter, it is important to gain understanding in the current context and working principle for the design. By uncovering how the design should interact with the user and its surrounding environment, new insights can be gained for design possibilities

The research objectives of the first phase are:

RO1: What is the influence of contextual elements on the product requirements?
RO2: What are the market opportunities relative to Euromate's product portfolio?
RO3: What are the ergonomic needs of the Personal Air Filter to create a positive user experience?
RO4: How are airborne transmissive diseases spread indoors, and how can a Personal Air Filter reduce the spread?
RO5: How do air purifiers work, and what method is most effective for filtering viruses?

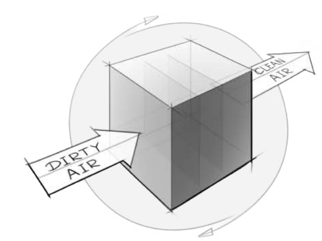
1.3.2 - Scope

Figure 6 gives an overview of the relevant research areas of the personal air filter. There are three main levels that describe the project architecture; context (meta), product use (macro), and performance (micro).



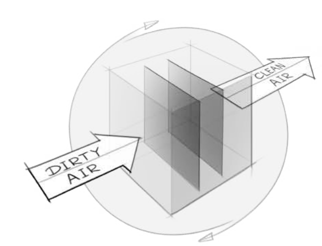
CONTEXT

- Office Context
- Existing Ventilation Systems
- Euromate
- Air Purifier Market
- User Needs
- Airborne Transmissive Diseases



PRODUCT USE

- User Experience
  - Use
  - Functionality
  - Actions
- Ergonomics
  - Air Quality
  - Noise
  - Temperature



PERFORMANCE

- Filtering Viruses
- Fans
- Clean Air Delivery Rate
- Positioning
- Optimization

Figure 6

Overview of relevant research areas of the Personal Air Filter project. Source: Author

1.4 - Methodology

The graduation projected is structured in four phases based on an integrated design approach as described in the Delft Design Guide (van Boeijen et al., 2020).

Discover identify, research, and understand the background, context, and problem areas.

Define and limit a clear problem that needs to be solved.

Develop ideas and concepts for the solution to the problem.

Deliver a validated design outcome.

Figure 7 shows where the different stages are applied to the project, as well as the relevant chapters and design methods used.

During the project, a range of design methods and tools were used to gather insights, create ideas, develop the concepts and validate the design. A User-Centered Approach[4] was taken because much of FLEX/design's and Euromate's previous work was focused on product performance. Taking the usability as a key driver of the project gives a new perspective to the problem at hand. Ultimately, the success of the design is determined by whether the product is comfortable to use while functioning as intended.

[4]
User-centered design is an approach that places the needs, preferences, and experiences of the end user at the forefront of the design process.

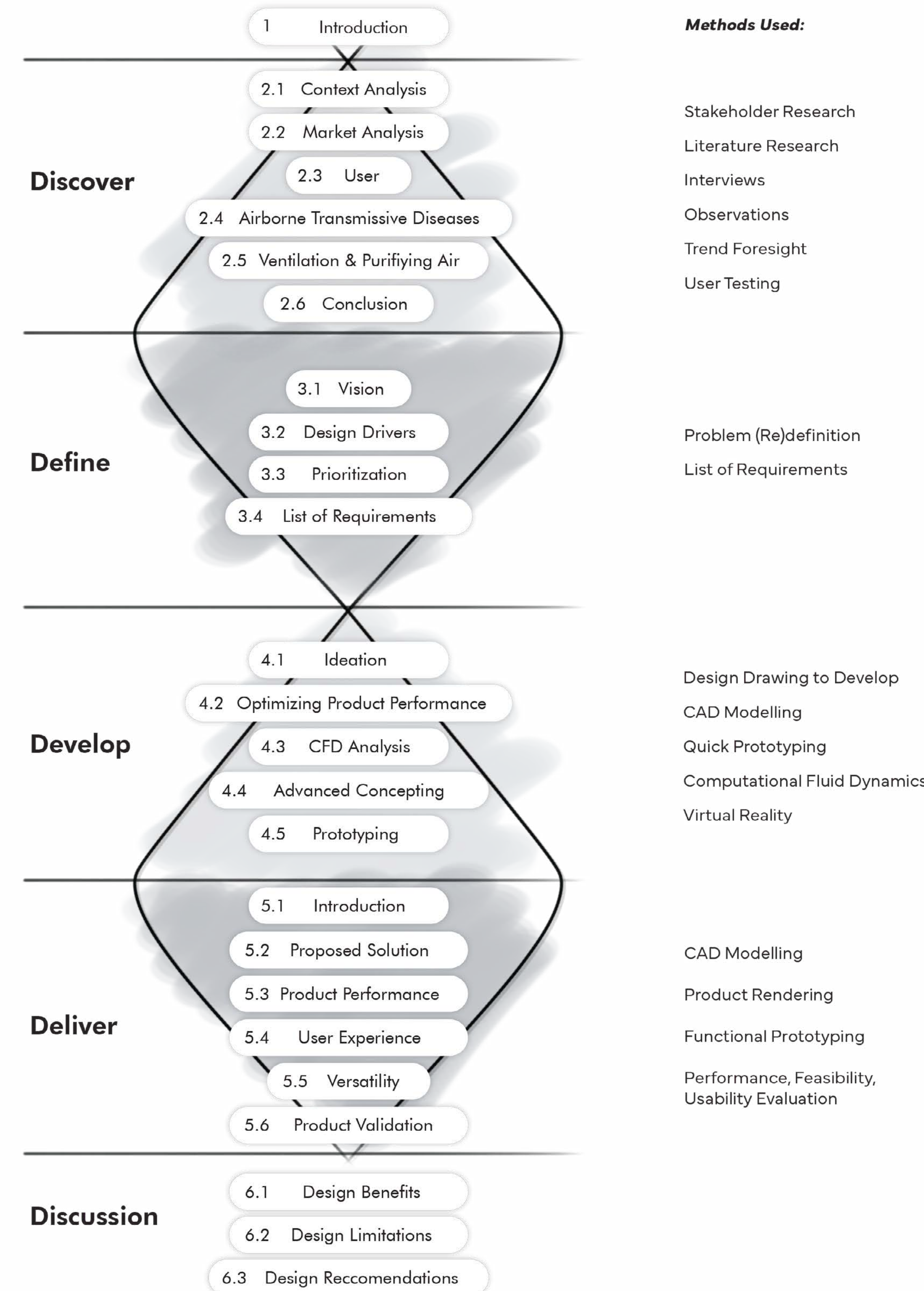


Figure 7
Double Diamond design approach applied to corresponding chapters and design methods used.
Source: Author

CHAPTER TWO

DISCOVER

The discovery phase shapes the basis of the problem synthesis. The office context is explored to gain an understanding as to what situation is most valuable to design for. Subsequently, a target scenario is analyzed to indicate the possibilities and restrictions for the placement of the Personal Air Filter. Employee needs are further elaborated to gain an understanding what common problems relevant to the personal air filter need to be solved.

To understand how the Personal Air Filter should interact with aerosols and the environment, a background about airborne transmission of viruses and the effectiveness of existing ventilation methods are explored.

RO1: What is the influence of contextual elements on the product requirements?

RO2: What are the market opportunities relative to Euromate's product portfolio?

RO3: What are the ergonomic needs of the Personal Air Filter to create a positive user experience?

RO4: How are airborne transmissive diseases spread, and how can a Personal Air Filter reduce the spread?

RO5: How do air purifiers work, and what method is most effective for filtering viruses?

2.1 - Office Context Analysis

The general target group for the Personal Air Filter are desk areas in offices. A variety of contexts were discussed together with the client, such as classrooms or hospital wards, however offices are more fitting with Euromate's clientele. Furthermore, offices have enough financial resources and therefore the largest potential for commercial success (personal communication, 2022). Subsequently, the project was oriented towards a Personal Air Filter for offices.

For the largest possible impact, the opportunity areas in offices were explored by understanding what area in the office has most potential. Furthermore, an empirical study on office archetype and desk configuration was done as to design for an appropriate scenario. Interviews were conducted with an occupational hygienist and an interior architect specialized in office design for creating a deeper understanding of the problems and possibilities. The target scenario was analyzed through an environment overview for insights in placement and restrictions.

2.1.1 - Office Area

The average Dutch employee spends around 260 working days, and 2,080 hours per year at work (How Many Work Days in a Year?, 2022). According to the Center for People and Buildings (CfPB) approximately 60% of the time of an average knowledge worker is spent at the desk (general work, undisturbed work, and interactive work) as seen in figure 8 (A. Boerstra et al., 2017). The desk area is therefore at a high risk of infection.

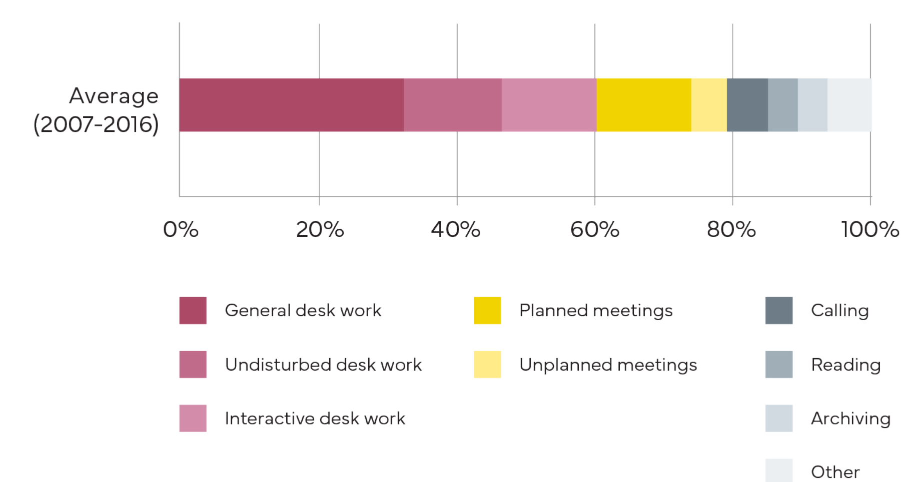


Figure 8

Activities of the knowledge worker (A. Boerstra et al., 2017)

2.1.2 - Empirical Study Office Archetype

[5]
Delftechpark is a business park with knowledge-oriented companies

An empirical study was conducted at the Delftechpark[5] in Delft, the Netherlands. Eight offices were observed to gain an understanding of the context for which the product is designed. Observations were done to look for commonalities across offices. Furthermore, discussions with employees were conducted to get an understanding to how offices approached Corona restrictions in the past and now. For the results of this discussion see Appendix C.

Results from the empirical study show that employees typically sit in a desk configuration opposing each other (figure 9). The desks are typically set-up in islands of two, four or six, with sometimes a few of these being unoccupied. An employee explained that these are available for new employees, or when somebody needs a flexible workspace (personal communication, 2022). Desks configurations where employees do not face one another are uncommon but do exist. It was also observed that the desks are typically rectangular. According to an ergonomist, these are used in most offices as they provide the best posture as opposed to curved desks, which were not observed (personal communication, 2022).

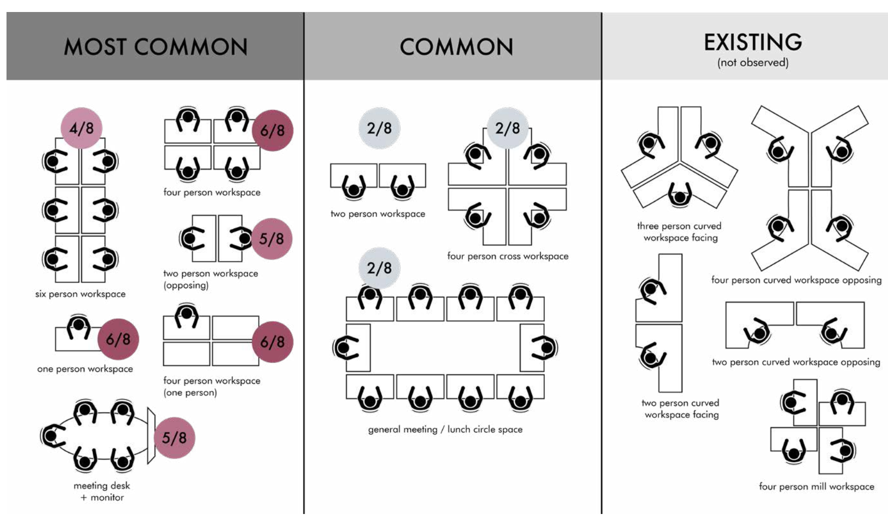


Figure 9
Desk setups observed during empirical study at Delftechpark, ranging from most common, common, to existing (not observed). Source: Author

The range of objects on the tables (seen in figure 10) differ vastly from office to office, but typically include a laptop, monitor, keyboard, mouse, and miscellaneous objects (paper, pens, glasses, etc.). These can potentially interfere with the Personal Air Filter, so it should be considered. Chapter 2.1.3 (target scenario) describes the context in more detail.

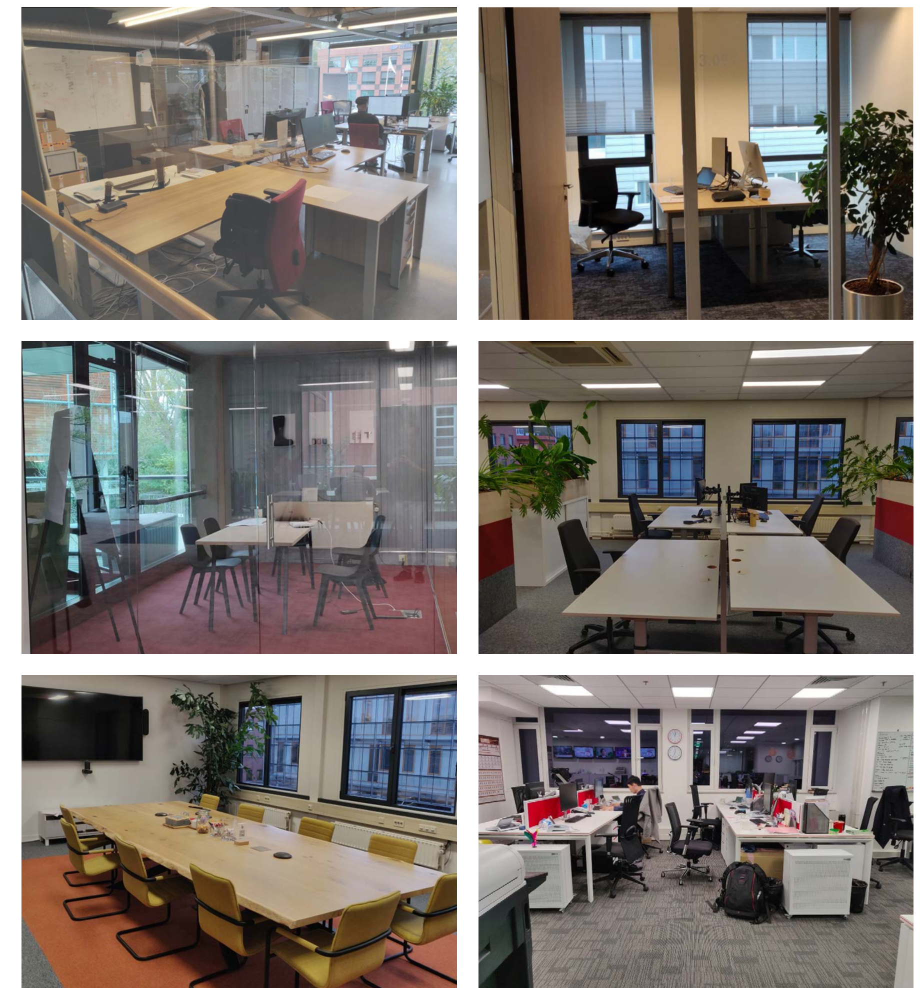


Figure 10
Collection of images from various office during empirical study at Delftechpark. Source: Author

2.1.3 - Target Scenario

The sketch in figure 11 is a scenario sketch of the relevant context for which the Personal Air Filter is designed to clarify opportunity areas and restrictions. The sketch shows an archetypical working area today for knowledge workers such as desk setup and placement of computers/laptops, power socket placement, etc. Factors that can influence the placement of the Personal Air Filter, such as the desk types, power supply will be further discussed.

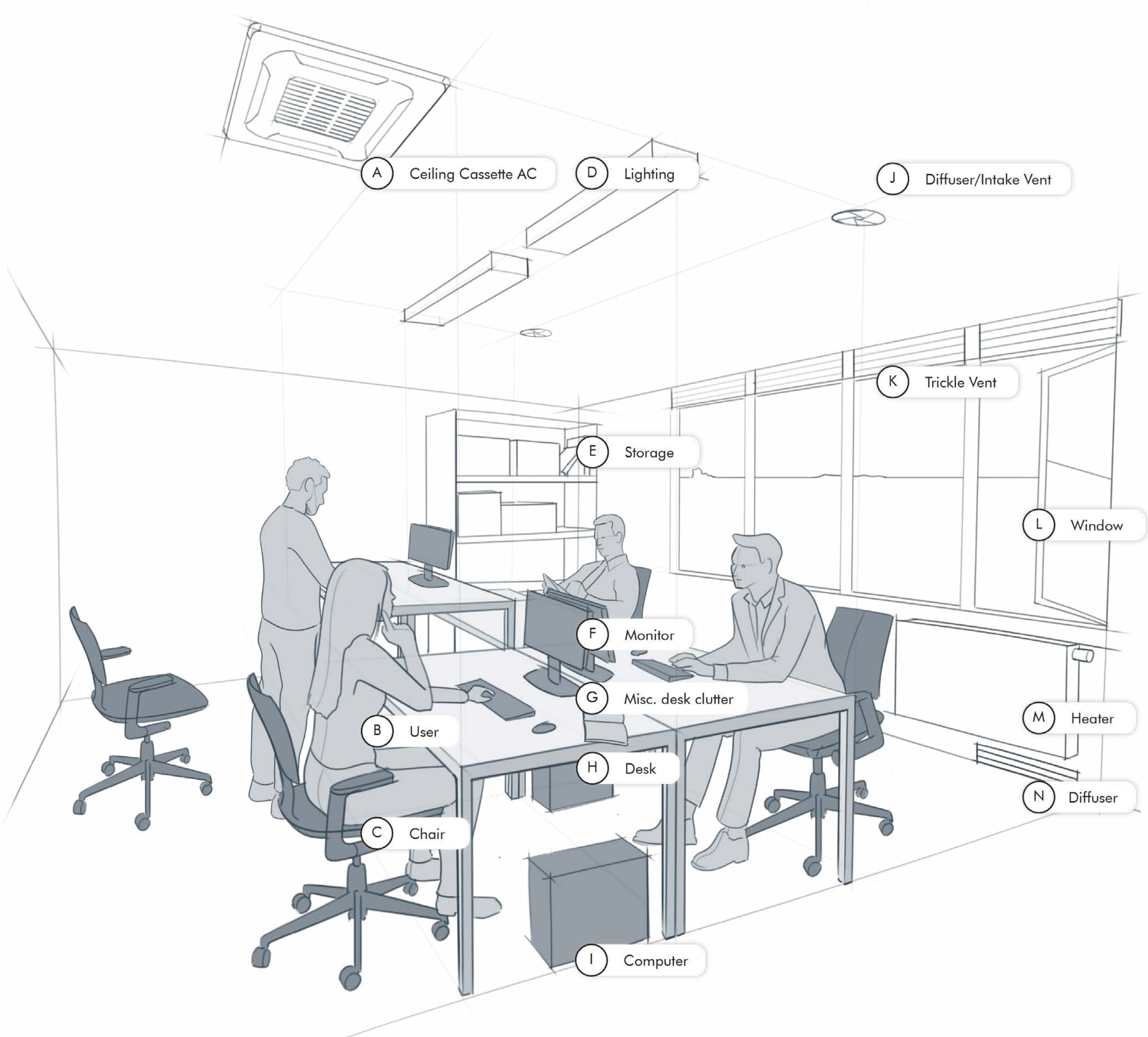


Figure 11
Context overview for the environment the Personal Air Filter will be implemented in. Source: Author

Desk Types

With an increased attention to posture, desks that are height adjustable are more commonly used today. The use of height adjustable desks has increased by 30% in Europe in the last five years (Fountain, 2022). This includes desks that can be installed at a specific ergonomic height per person or that can adjust electronically through the use of a button. Moreover desk height may differ for sitting desks. As a result, desk height should be taken into consideration for the context. Other desks not shown in the sketch are also available, such as system desks or workstations. Figure 12 shows a small selection of the variety of desks available.

Figure 12
Single desk (top-left), two person (top-right), system desk (bottom-left) long system desk/workstation (bottom-right)

Power supply

During an interview with an interior architect from TopInterieurOntwerpers[6], power sockets are generally available around the desk area. Modern system desks typically have sockets incorporated in the desk or underneath. Power sockets are also found incorporated in the walls, usually close to the floor. Retrofitting an air filter suspended from the ceiling may introduce a challenge of supplying electricity without having cables visible (personal communication, 2022).

[6]
TopInterieurOnterpers is an architect firm situated in Boskoop, the Netherlands, with expertise in office interior design.

2.1.4 - Office Trends

Over the years, the desks in offices have become smaller because monitors and computers take up less space than before (personal communication, 2022). As a result, the employees sitting opposite one another is sitting closer within the range of respiratory droplets and aerosols. The largest focus is on filtering between opposing employees, since the propagation of droplets is conical (Yin et al., 2022). The traveling distance of respiratory droplets and aerosols in an office setting where two employees are sitting opposite of each other suggests the exposure risk of the non-infected individual (figure 13).

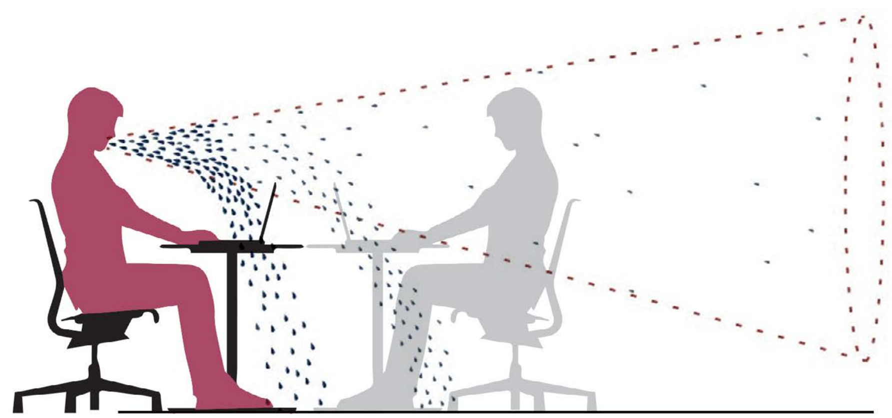


Figure 13
Droplet and aerosol trajectory with individuals working opposite of each other (distances may not be represented accurately) source: Author

Future Office

Office are currently asking more often for flexible layouts that enable for flex working, where people do not have an assigned workspace and may sit at different desks on different days. Furthermore, the styling is becoming softer as there is a general trend to make offices more home-like; "the office has become a space where people meet as opposed to just work" (personal communication, 2022). On the other hand, offices are taking a step away from the open-floor planning as studies suggest it may be hampering employee productivity (Kim & de Dear, 2013). This shift towards more friendly but secluded environments is also noticeable in future office design and offices compared to the past (figure 14). Besides filtering the Sars-CoV-2 virus, the Personal Air Filter should fit in an environment where the user feels comfortable and at home.

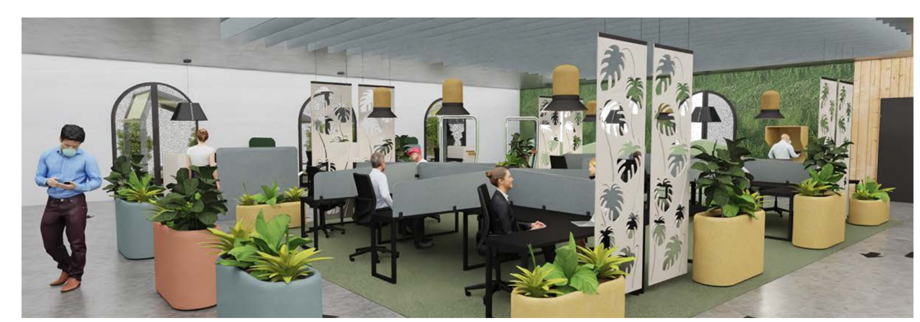


Figure 14
Cubicle office in the 1960s (top) (Saval, 2014), typical open office today (middle) (Shriver, 2022), future concept of office design (bottom) (Felix, 2020).

2.1.5 - Office Context Analysis Key Insights

RO1: What is the influence of contextual elements on the product requirements?

- Employees (knowledge workers) spend 60% of their time at the desk, which are therefore the area with a high risk of transmitting airborne diseases.
- Desks are more commonly configured to sit opposite of each other, creating a high-risk area for transmission via aerosols.
- The device must fit within the intended environment to be viable.
- The personal air filter should be compatible with a wide variety of existing desks.
- Placement of power sockets should be considered, as they are typically available near walls and underneath/in the desks.
- As offices are becoming more friendly in styling and home-like, the Personal Air Filter should compliment this.
- Offices are transitioning towards more secluded but flexible workspaces, therefore the Personal Air Filter should be usable by different individuals to their own needs.

2.2 - Euromate & Market Analysis

The current product portfolio of Euromate is analyzed as it shows what the possibilities and restrictions for the Personal Air Filter are. Furthermore, the air purifier market is analyzed to give an overview of what exists, what current trends are, and where the opportunity areas lie. For an analysis of all stakeholders, see Appendix E.

RO2: What are the market opportunities relative to Euromate's product portfolio?

2.2.1 - Euromate

Euromate air cleaners are intended as an addition to an existing ventilation systems, meaning that the ventilation system does not have to be adapted. All of their products operate on a plug-and-play basis, which means they can be installed without the need for dismantling work (Professionele Luchtreiniging & Luchtfiltering | Euromate, n.d.). Two of their products are specifically oriented to improving air quality and filtering viruses, namely the Vision Air Blue Line and the Pure Air Shield 3300. Other products, like the Dust Free Industrial 8500, are intended to filter dust in industrial settings.

Vision Air Blue Line

Euromate developed the Vision Air Blue Line for both offices, schools, nursing homes, and more. The Vision Air is a plug-and play unit can also be mounted on a stand (figure 15), and enables one or two units two be installed in ceilings (figure 16). The design is widely applicable due to the range of possible filter combinations for specific pollutants. These include filters intended for viruses and bacteria, particulate matter, harmful gasses, smoking gasses, and odors. There is also an option available with UV-C intended for dentists, hospitals, nurseries and the food industry. Furthermore, optional fragrance cartridges (FreeBreeze) can be added to spread a fresh odor (figure 17). The OLED display allows for the adjustment of settings, such as using a timer or the passive infrared (PIR) sensor to automatically turn the device on or off (figure 18).

Figure 15
Euromate Vision Air Blue Line on Stand (Professionele Luchtreiniging & Luchtfiltering | Euromate, n.d.)

Figure 16
Euromate Vision Air Blue Line mounted in an office ceiling (Professionele Luchtreiniging & Luchtfiltering | Euromate, n.d.)

Figure 17
Euromate Vision Air Blue Line FreeBreeze (Professionele Luchtreiniging & Luchtfiltering | Euromate, n.d.)

Figure 18
Euromate Vision Air Blue Line OLED display (Professionele Luchtreiniging & Luchtfiltering | Euromate, n.d.)

Pure Air Shield 3300

The Euromate Pure Air Shield 3300 (figure 19& 20) is a standalone air purifier intended for large spaces from $200m^2$ which filters dust, viruses and bacteria. It is equipped with a HEPA-14[7] filter and carries out 5 ACH to ensure safe and clean air for the surroundings. The ACH can be adjusted to fit the surroundings such as how many people occupy the space, the activity performed by those people, and what ventilation system is in place.

[7]
HEPA-14 is within the highest tier of HEPA air filtration and are considered medical-grade. HEPA-14 removes 99.995% of particles 0.3 microns in diameter.

Figure 19
Euromate Pure Air Shield 3300 in office environment (Professionele Luchtreiniging & Luchtfiltering | Euromate, n.d.)

Figure 20
Euromate Pure Air Shield 3300 (Professionele Luchtreiniging & Luchtfiltering | Euromate, n.d.)

Dust Free Industrial

Euromate also produces other air purification devices for industrial purposes, shown in figure 21 & 22, such as the HF-Series Industrial air cleaner, SF-Series Kitchen Air Filtration, and Dust Free Industrial 8500 . The latter device is intended for reducing dust in production plants, warehouses and workshops.

The Dust Free Industrial 8500 is especially interesting as there is a Product as a Service (PaaS) system in place to replace filters when necessary and maintain the device. Furthermore, the air cleaning capacity can be optimized due to the adjustable grid[8].

[8]
The devices work together in a grid system to create an airflow that improves overall filtering efficiency.

Figure 21
Euromate Dust Free Industrial 8500 in warehouse (Professionele Luchtreiniging & Luchtfiltering | Euromate, n.d.)

Figure 22
Dust Free Industrial 8500 (Professionele Luchtreiniging & Luchtfiltering | Euromate, n.d.)

2.2.2 - Air Purifier Market

Figure 24 shows an overview of a selection of air purifiers grouped in Covid-19 oriented, office context, and general use such as at home or other settings. From the visual and parallel research, it can be deduced that air purifiers are rarely purpose designed against airborne transmissive diseases and that there is little diversification in products.

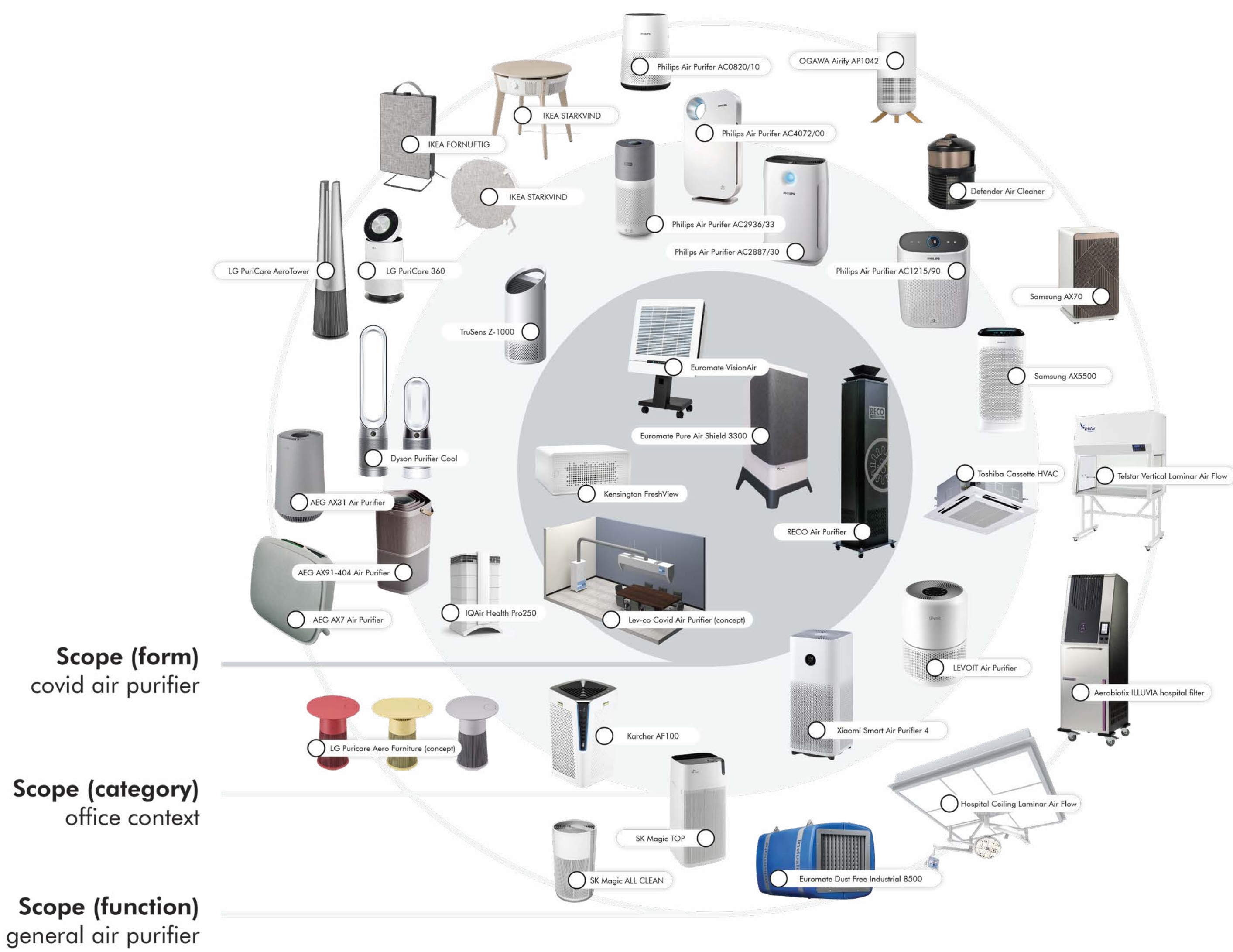


Figure 24
Air Filter Market overview grouped in 'covid air purifier (form)' 'office context (category)', and 'general air purifier (function)'. Source: Author

Purpose Designed

According to Morawska, a local air filter needs to be purposely designed to control risk of airborne infection (2020), however the air purifiers marketed to reduce in transmission of airborne transmissive diseases is limited. This may be due to the level of proof necessary to make such a claim. Nonetheless, many of these products are not purpose designed for a specific context, instead having an archetypical form.

An interesting product that is purpose designed is the Lev-co Covid Air Purifier (figure 25). Though it is still a concept and arguably not the most user centric design, the form is optimized to supply fresh air to the people sitting at the desk. The local exhaust ventilation drives away contaminants from the desk area towards the air filter, which is placed far away from the sitting area for noise reduction (Air Purifiers for Covid | Stand Alone Solutions, n.d.).

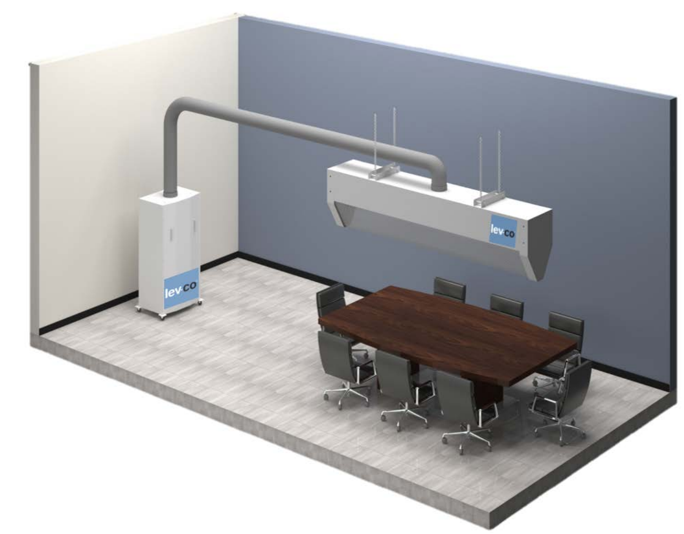


Figure 25
Lev-co Local Exhaust Ventilation Air Purifier (Air Purifiers for Covid | Stand Alone Solutions, n.d.)

Diversification

From the 'office context' group, indicating the product category the Personal Air Filter will compare with, it is evident that there is little diversification. The archetypical air purifier is either rectangular or round, with intake from the side and exhaust at the top. The air purifiers are typically standalone units that can placed either in the room or on the desk. Some brands are diversifying by adding stylistic features, such as Dyson, Philips and LG. Nonetheless, the devices can be considered 'standard' air purifiers.

A new emerging trend in diversifying the air purifier market is the integration of the device in furniture. Though the IKEA STARKVIND is intended for use at home, it is a good example of how the bulky components are worked away underneath the table. Other brands are taking notice too, LG for example proposed the Puricare Aero Furniture concept which functions as a table, lamp, phone charger, and air purifier (LG, 2022). A new product proposed for offices, the Kensington FreshView, is a screen stand that doubles as an air purifier. It can also heat the air to improve comfort of the employee (Your Office Needs an Air Purifier With a HEPA Filter, 2020).

Figure 26
IKEA STARKVIND (left), LG Puricare Aero Furniture (middle), Kensington FreshView Air Purifier (right)

2.2.3 - Euromate & Market Analysis Key Insights

RO2: What are the market opportunities relative to Euromate's product portfolio?

- Air cleaning capacity can be optimized with multiple devices working together like the Dust Free Industrial 8500.
- The air purifier market lacks purpose designed air purifiers for Sars-CoV-2 and offices (though regular HEPA air purifiers do also work).
- Air purifier trends see emergence of integrating the purifier in furniture.

2.3 - User

The needs of the office and its employees are explored to get a better understanding what aspects of the design for the Personal Air Filter are important. Findings from the interview with the interioir architect from TopInterieurOntwerpers and with an office employee from Philips were conducted to get these insights.

RO3: What are the ergonomic needs of the Personal Air Filter to create a positive user experience?

2.3.1 - Office & Employee Needs

In the interview with the interior architect, the needs of offices undergoing a refurbishment were discussed. According to the them, offices often have common aspects that need to be resolved. Some are more relevant to the Personal Air Filter, as these may influence the product requirements. The topics acoustics, heating, and energy are therefore further discussed as these have the most direct impact to air purification in offices.

Acoustics: desk spaces should be quiet for improving performance of employees
Heating: heating can be unevenly distributed within the offices or differ per person
Operational Costs: products with high operational costs are undesirable

Acoustics

Acoustics are a common problem across almost all offices. Noise from employees or machines distract employees and result in efficiency loss. Accordingly, improving sound insulation is the most common desire during renovations as "10/10 offices they ask for this" (personal communication, 2022). Typically, the architect introduces new carpets, sound insulating panels, and desk dividers to dampen the sound.

Unevenly Distributed Heating

As heating systems are commonly measured at a single point centrally managed, temperatures can differ per area. Improving heating systems involves installing/altering the heating system and can be costly. Furthermore, the desired temperature differs from person to person, which is further discussed in 3.2 (ergonomic needs).

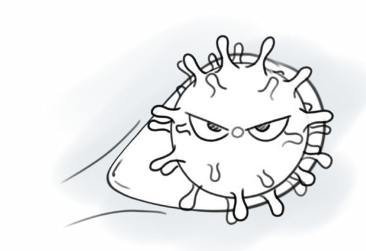
Operational Costs

With high energy prices today and a shift to an energy neutral society, there is a strong desire for energy efficient products. Products with a high energy use are changed for more efficient products to offset long-term operational costs. Air purifiers have operational costs such as running the fan and periodic replacement/maintenance of the filter. According to Bekö et al. "particle filtration is anticipated to lead to annual savings significantly exceeding the running costs for filtration (2008). However, economic losses resulting from even a small decrease in productivity caused by sensory pollutants emitted from used ventilation filters have the potential to substantially exceed the annual economic benefits of filtration" (Bekö et al., 2008). Therefore, it is of great importance that there is a working system in place to stimulate the maintenance of filters to prevent adverse effects.

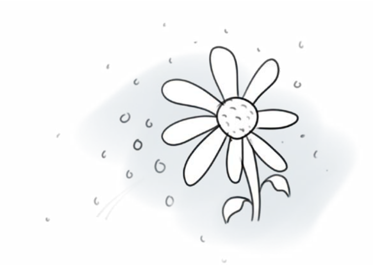
2.3.2 - Product Purpose

The product should be strategically oriented to fit the needs of offices and their employees to become a commercial success. In an interview with an employee with underlying health problems, the effects of the coronavirus pandemic in on well-being in the past and now were discussed. Though one would expect a certain level of fear to return to the office after a lockdown, the contrary came to light. To this person it is evident that fear and seclusion from society is no longer impacting their life significantly (personal communication, 2022). The empirical study at offices and an occupational therapist support this notion as preventing transmission of the Sars-CoV-2 virus alone is no longer enough to convince employers and faculty managers to install an air purifier (personal communication, 2022).

Instead, in collaboration with Euromate it was specified that the device should offer greater benefits to appeal to a greater set of needs of offices and employees. Air purifiers can also filter pollen and other allergens, therefore the Personal Air Filter should aim to do this effectively. Furthermore, needs like improving employee well-being could also be a unique selling point. These three purposes are shown in figure 27.



Must filter viruses to prevent the transmission of airborne transmissive diseases.



Should reduce the impact of allergies on workers.

Could improve worker comfort & well-being and thereby productivity.

Figure 27

Product purpose requirements for the Personal Air Filter derived from interviews with users, occupational hygienists, and interior office architects. Source: Author

2.3.3 - User Experience

The user experience is mapped for an existing air purifier to understand the product use criteria. What factors are important to the user, and how do these influence the user? Working with the air purifier running in the background, the user interface interaction, and the experience of changing the HEPA filter are elaborated on. These elements will also embody a large part of the user experience of the user with the Personal Air Filter, and consequently the criteria.

The AEG AX7 Air Purifier made by AEG was tested for the user experience. The goal of the study was to understand what aspects of the device creates a evoke positive or negative emotions. This product was selected as it is one of the quietest air purifiers on the market today (iF Design Award, 2021). The Junto Institute 'emotions and feeling' wheel was used by the participant to help identify the emotions/feelings during each phase. The air purifier was placed in the working environment within close proximity to the user, simulating the ideal situation for filtering aerosols nearby the user. During the working phase, the user worked for 30 minutes per ventilation rate. A total of four participants particpated in the test. The results of the study are summarized in figure 29. For the test setup and individual results per participant see Appendix D.

Figure 28
AEG AX7 Air Purifier (AEG, n.d.)

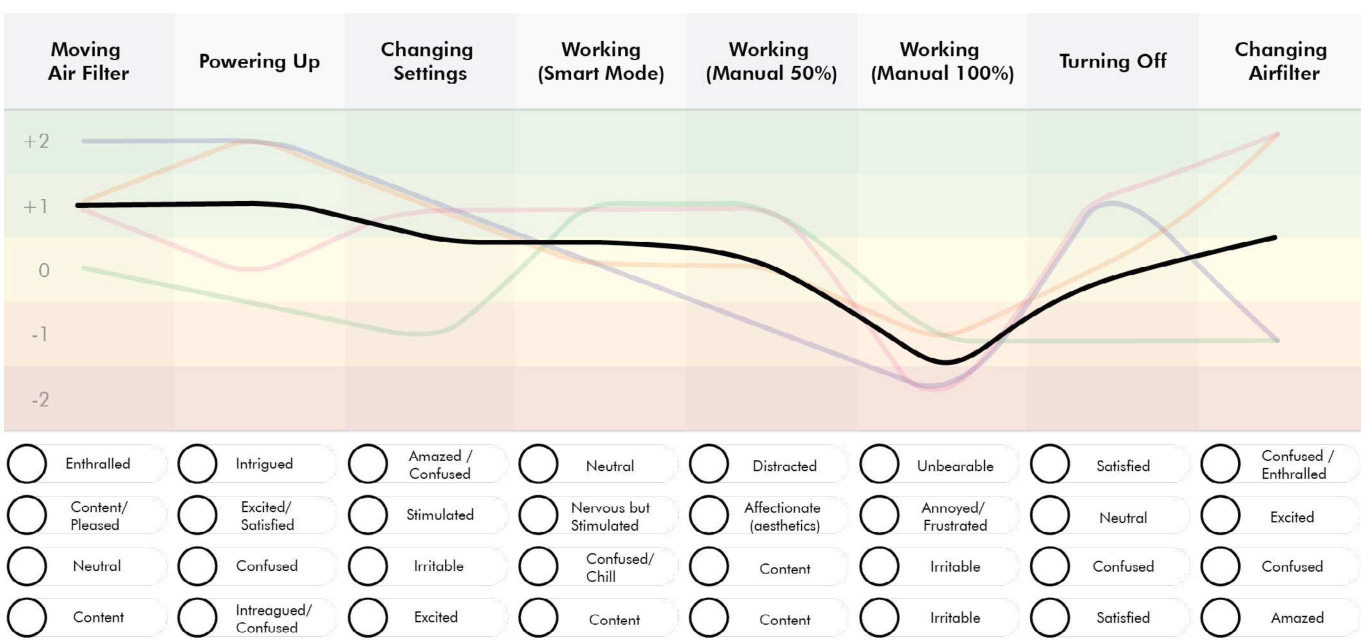


Figure 29
Summarized results of user experience test of AEG AX7 Air Purifier. Source: Author

Maximum Noise Level

The most noteworthy observation is the dip in satisfaction when the device was set at the highest ventilation rate 'manual 100%' producing approximately 70dB. For both the 'smart mode' and 'manual 50%' the level of noise was considered acceptable (40dB – 45dB), however anything louder than this would annoy or irritate the user. One participant found the level of noise at 100% cpacity unbearable and turned it to a lower level. The study indicates that there is a maximum level of noise acceptable around the 'manual 50%' before bothering the user.

A study by Bluyssen found that a mobile HEPA filter in proximity of the user produced 40 to 51dB measured at the user, which is significantly higher than the maximum legislative 38dB allowed for ventilation (note: not air purifiers) systems (Bluyssen et al., 2021; EN 16798-1, 2019). From this study, it can be concluded that the design should consider how to minimize noise while maintaining performance. Ideally, the device should produce less than 38dB and absolutely must not produce more than 45dB measured from the user's head.

Wind-Chill[9]

When the device was operating at the highest ventilation rate, multiple users experienced what they described as a cold sensation around the hands. "There was a wind flow over the table that was not very nice... my arms feel cold." The device creates a subtle but noticeable unpleasant wind flow over the table surface. Though the AEG AX7 is not intended to be placed on a table, it is demonstrated that the discomfort of 'wind-chill' should be minimized by placement in the final design.

[9]
Wind-chill refers to the cooling sensation experienced by the human body due to the combined effect of wind and cold temperatures. It describes how wind can increase the rate at which heat is lost from exposed skin, making the air feel colder than the actual temperature.

Changing the HEPA filter

The user interaction for changing the HEPA and carbon filter had a range of experiences. Steps for maintenance are shown in figure 30. The negative emotions were evoked by confusion as the orientation of the filters is not clear to every user. Though these are clearly marked with the right way up, a user suggested that "the HEPA should only fit one way." On the other hand, the magnetic front panel is easy and intuitive to remove, which amazed and excited the participants. The design of the Personal Air Filter should make changing the HEPA filter a desrable experience.

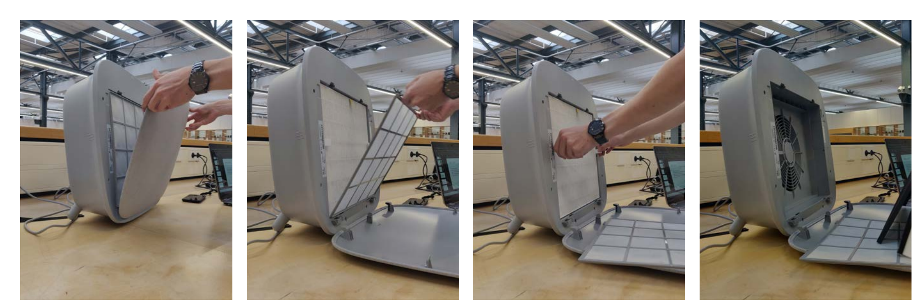


Figure 30
Removing/placing: (1) front panel, (2) protective screen, (3) HEPA filter, (4) carbon filter. Source: Author

2.3.4 - Ergonomic Needs

Ergonomic needs in the office from the employee's perspective is focused often on improving health and safety, by protecting individuals from accidents and injury. Focus on the employees' physical ergonomics are not in the scope of the research. Instead, the effect of better cognitive ergonomics can also improve productivity (Todd, n.d.). Literature research and discussions with an occupational hygienist were done to gain a better understanding of the topic.

Environmental Factors

From the perspective of the employer, the employees ideally perform at the highest level possible and are on sick leave as little as possible. The design should ensure that productivity is not hampered, orideally increases productivity. According to a literature survey, the environmental factors, most relevant to the Personal Air Filter, that influence productivity and sick leave in offices are thermal indoor climate, air quality, sound/acoustics, and artificial/day light, summarised below (van Dijken & Boerstra, 2010). Other factors that influence productivity are shown in figure 31. For an in-depth research study for the environmental factors see Appendix F.

Figure 31
Factors influencing productivity based on Boerstra et al. (n.d.). Source: Author

Thermal indoor climate (temperature)

Thermal comfort in offices is influenced by factors like overheating and undercooling, leading to individual experiences of thermal satisfaction. Local discomfort, such as draught or temperature differences, can contribute to thermal dissatisfaction. Productivity is optimal within a temperature range of 20-25 °C, with a decline of 2% for every 1°C increase beyond 25 °C (Seppänen et al., 2006). Undercooling negatively affects performance and finger dexterity (van Dijken & Boerstra, 2010). Employee control over temperature has a positive impact on comfort and productivity, as shown by studies on local temperature control systems and thermostat knobs (van Dijken & Boerstra, 2010; Ye et al., 2005).

Air Quality

Air quality in offices is influenced by fresh air supply and sources of contamination, and improving both factors can enhance productivity. Good ventilation not only helps reduce the spread of diseases like SARS-CoV-2 but also promotes employee well-being, satisfaction, lower absenteeism rates, and decreased exposure to air pollutants (Sundell et al., 2011). Increasing the airflow rate per square meter in an office space leads to higher productivity, with a 6% increase observed when supplying 20 l/s of fresh air compared to 4 l/s (Kasonen & Tan 2004). Regularly changing air filters is also recommended to maintain air quality and prevent negative effects on health, comfort, and performance.

Noise

Noise in office environments, whether intermittent or continuous, can impact employee performance and well-being. Intermittent noise, such as phone conversations, can have a negative effect on self-estimated performance, while continuous noise from ventilation systems has a weaker impact. Unpredictability of noise is more influential than its decibel level i.e. a varying noise intensity is more influential than a consistent noise. Nonetheless, legislation ensures office noise levels remain below 38 dB continuous sound level caused by building services.

Control

The effect of control by the individual on the environmental factors may also have an impact on the perceived comfort and productivity (Boerstra et al. 2015). The control as the moderator model by Boerstra et al. 2015 in figure 32 shows how three types of control, available, exercise, and perceived, can possibly evoke a positive response from the user. "The main assumption is that human responses to sensory stimuli are modified when those exposed have control over the stimuli" (de Dear & Brager, 1998).

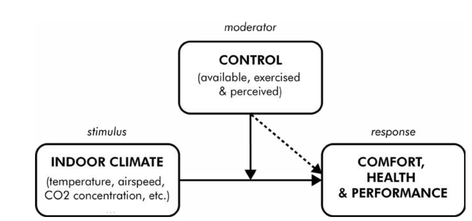


Figure 32
Control as the moderator model (A.C. Boerstra et al., 2015)

2.3.5 – User Key Insights

RO3: What are the ergonomic needs of the Personal Air Filter to create a positive user experience?

Needs

- Common relevant problems that are solved by interior architects in offices are acoustics and heating.
- The Personal Air Filter could improve acoustics and local heating to make the product more desirable.
- Increase in productivity offsets operational cost of mobile air purifier if filters are periodically maintained
- The device should filter viruses to prevent the transmission of airborne transmissive diseases, which could reduce the impact of allergies and spread of diseases on workers, and could improve worker comfort and well-being and thereby productivity

Ergonomics

- Environmental factors that influence sick-leave and productivity include, amongst others, thermal indoor climate, air quality, sound/acoustics, and artificial/day light.
- People that experience local discomfort are most commonly doing inactive activities such as desk work.
- Most occurring problem for thermal dissatisfaction is draught.
- Good ventilation correlates with better health, higher levels of employee satisfaction within the office, lower rates of absence from work, and less exposure to a range of air pollutants.
- Bad maintenance of HEPA filters can reduce productivity.
- Unpredictability of noise rather than the decibel level results in the unfavorable reactions of office workers to air purifiers.
- Available, exercise, and perceived control, can evoke a positive response from the user.

2.4 - Airborne Transmissive Diseases

For a better understanding of how the Personal Air Filter should filter aerosols and large respiratory droplets, literature research is conducted. A summary of the most relevant information is presented, such as the role of ventilation in reducing transmission and what environmental factors increase the risk of infection.

RO4: How are airborne transmissive diseases spread, and how can a Personal Air Filter reduce the spread?

2.4.1 - Reducing Risk of Transmission by Ventilating

According to recent research, many workplaces do not withstand recommended ventilation precautions increasing the risk of virus transmission (Morawska et al., 2020). To reduce the risk of airborne transmission, Morawska suggests:

*" To **supplement existing ventilation with portable air cleaners** (with mechanical filtration systems to capture the airborne micro- droplets), where there are areas of known air stagnation (also referred to as stratification), which are not well-ventilated with the existing system, or **isolate high patient exhaled airborne viral loads** (e.g. on COVID-19 cohort patient bays or wards)."*

Other engineering controls suggested by Morawska et al. (2020) can be found in Appendix G.

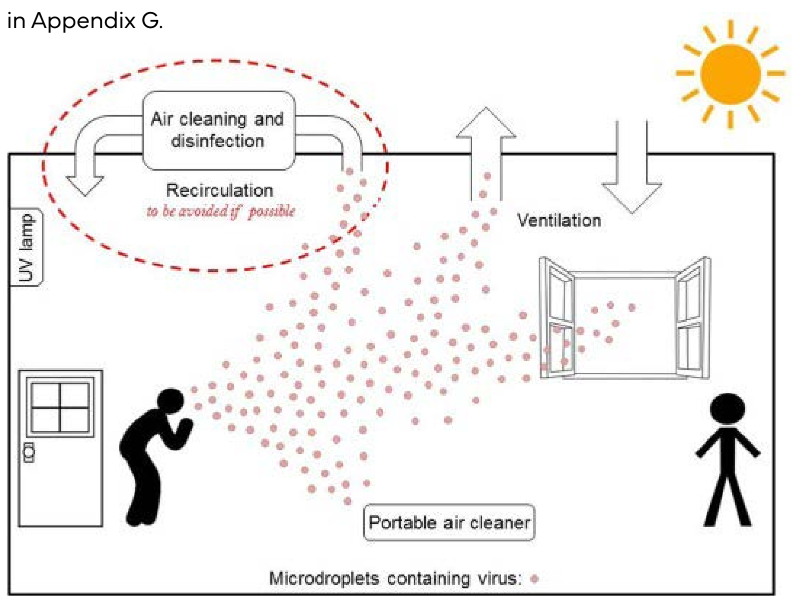


Figure 33
Engineering level controls to reduce the environmental risks for airborne transmission (Morawska et al., 2020)

Respiratory Droplets, Aerosols, Fomites

Currently, there is ongoing research world-wide about the transmission of SARS-CoV-2. There are three known causes for transmission; large respiratory droplets, contaminated surfaces, and aerosols (figure 34).

1. Direct transmission of virus carrying droplets when in close vicinity by coughing, sneezing or talking (Chen et al., 2020);
2. Indirect transmission via deposited or transmitted infectious droplets via surfaces, commonly referred to as fomites (Chen et al., 2020);
3. Airborne transmission through virus carrying small airborne droplets (also named 'aerosols') emitted by infected individuals (Prather et al., 2020).

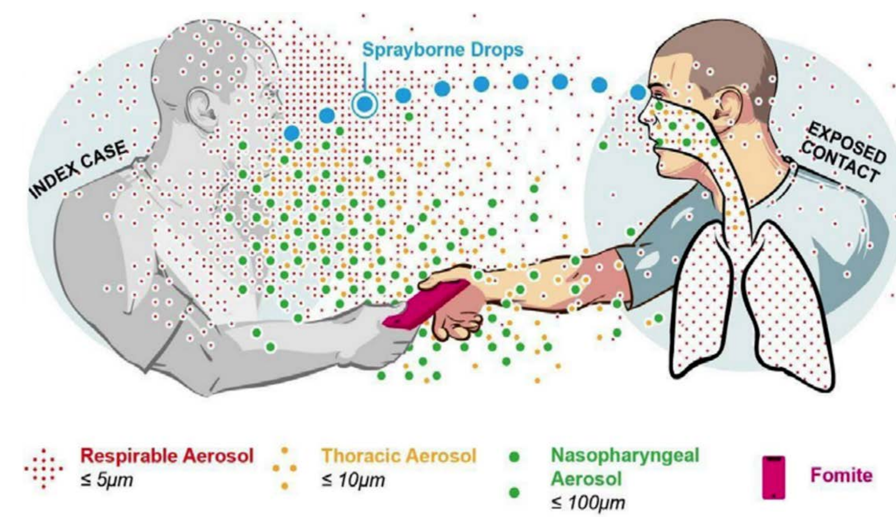


Figure 34
Three known methods of transmission of SARS-Cov-2 virus, droplets (blue), fomites (pink), aerosols (red, yellow, green).

For the third mode of transmission, airborne transmission, recent studies indicate that in spaces with insufficient and ineffective ventilation the risk increases (Miller et al., 2021; Nishiura et al., 2020). As a result, besides vaccinating, social distancing, wearing facemasks, washing hands, and cleaning surfaces, the World Health Organisation (WHO) also recommends increasing the amount of ventilated air in crowded spaces and filtering contaminated air to reduce airborne transmission of SARS-Cov-2 (WHO, 2021).

"It is concluded that there is no evidence to support the concept that most respiratory infections are primarily associated with large droplet transmission, and that small particle aerosols are the rule, rather than the exception, contrary to current guidelines" (REHVA, 2020a).

Medical literature is currently suggesting a paradigm shift in the knowledge about infectious aerosols. Therefore, the Personal Air Filter will focus heavily on filtering for aerosols that can contain Sars-CoV-2 and other viruses.

Environmental Factors for Aerosols

Time and distance, temperature & humidity, concentration, number of people in a room, and exposure time are environmental factors influencing the probability of infection. These give insight in the placement and requirements of the Personal Air Filter. For example, the thermal plumes[10] shown in figure 35 need to be taken into account when designing the Personal Air Filter. For more information regarding the environmental factors, see Appendix H.

[10]
Thermal breath plumes refer to the warm exhaled air that is released from the human respiratory system during breathing. When we exhale, the air leaving our lungs is warmer than the surrounding ambient air. This temperature difference creates a thermal gradient, causing the exhaled air to rise and form a plume or column of warm air (Bhagat et al., 2020).

(a) (b) (c)

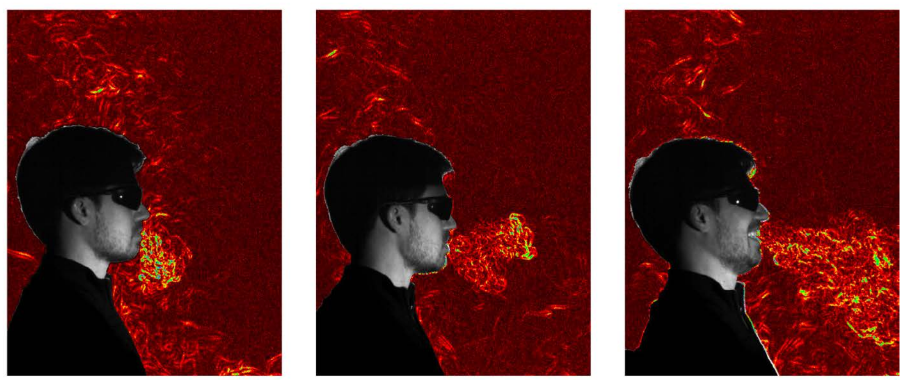


Figure 35
Differential synthetic schlieren images of the thermal plumes produced by a person in a quiescent environment. In panels (a–c) no mask is worn, The subject is (a) sitting quietly breathing through their nose, (b) saying 'also' when speaking at a conversational volume and (c) laughing (Bhagat et al., 2020).

2.4.2 - Airborne Transmissive Diseases Key Insights

RO4: How are airborne transmissive diseases spread indoors, and how can a Personal Air Filter reduce the spread?

- Three methods of transmission are droplets, fomites, aerosols
- Risk of transmission increases in spaces with insufficient and ineffective ventilation
- Recirculation of air in existing ventilation systems should be avoided
- Additional air purifiers can improve air quality locally, but need to be purposefully designed to prevent adverse effects such as further spread of pathogens through the room.
- The air filter should focus primarily on filtering aerosols
- The placement of the air filter is crucial considering the influence of environmental factors on the propagation of respiratory droplets and aerosols
- The air filter should be placed in the breathing zone of the user and consider thermal plumes to optimize efficiency
- The device should have the largest capture area possible
- Reducing concentration of aerosols with Sars-CoV-2 will reduce the risk of infection
- Areas with longer exposure time increase probability of transmission of airborne transmissive diseases

2.5 - Ventilation & Purifying

The device will have to function with a variety of ventilation methods used in office. Airflows can interfere and cause adverse effects. For this, research into common ventilation methods is done to give an overview in the expected problems. Furthermore, the effectiveness against virus transmission of each method is reviewed for a better understanding of the opportunity areas.

RO5: How do air purifiers work, and what method is most effective for filtering viruses?

2.5.1 - Ventilation Methods

Ventilation is the process of the process of changing or replacing air in any space to provide high indoor air quality (ISO, 2017). To design how the Personal Air Filter will interact with the environment, it is of importance to understand the different types of ventilation that exist and will interact with. Working principles from these ventilation methods and strategies may also be relevant to how the Personal Air Filter will work.

Ventilation Strategies

Lipinski describes the three main strategies for ventilation; recircling ventilation, mixing ventilation, and displacement ventilation (2020). These are elaborated and analyzed for effectiveness against the transmission of Covid-19 in Appendix I. Each uses one or multiple of the ventilation principles natural ventilation, mechanical ventilation, hybrid ventilation, spot ventilation, and task ambient conditioning. Certain strategies are more effective than others in reducing the risk of transmission of airborne transmissive diseases.

Mixing & Recircling Ventilation

For mixing and recircling ventilation, air is blown at high velocity through vents into the room, creating a turbulent airflow as seen in figure 36. Interference of airflows between building ventilation and the device may pose to be a challenge and should be further tested during the development stage. Both recircling and mixing ventilation strategies are counterproductive in reducing the risk of transmission of airborne transmissive diseases. Aerosols are spread further than through natural propagation and can infect more people (Lipinski et al., 2020). There is an opportunity area in retrofitting purpose designed Personal Air Filters in offices with recircling and mixing ventilation to reduce concentration of aerosols.

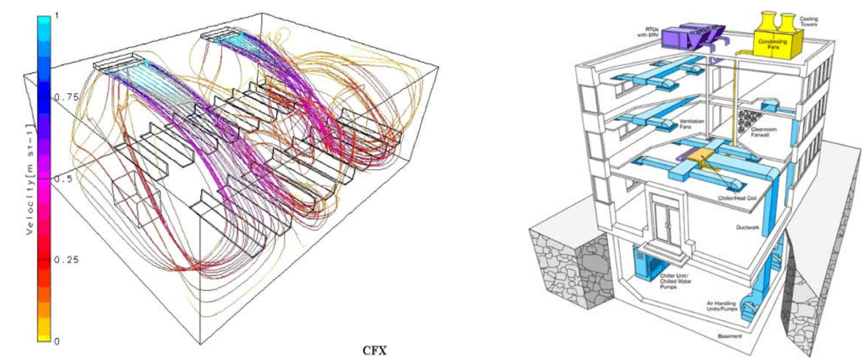


Figure 36
Recircling ventilation: CFD of a typical split AC in a typical lecture room (Lin, 2015) (left).
Mixing ventilation: diagram of a standard AHU system with ventilation on the ceiling (Willwerth, 2013) (right)

Displacement Ventilation

Displacement ventilation on the other hand is the most effective ventilation strategy combating coronavirus in public buildings as there is a calm directional airflow that prevents aerosols to mix into the room (Lipinski et al., 2020). In recent research, Bluyssen suggests including personal ventilation as a new strategy to improve indoor air quality (2020). Working principles of displacement ventilation can potentially be applied at a smaller scale to the personal air filter as it proven to work on a large scale.

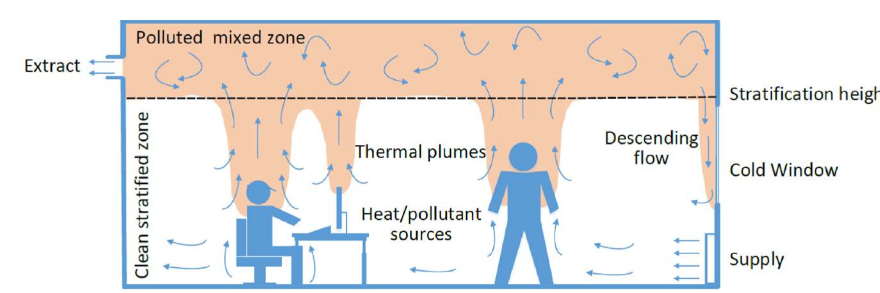


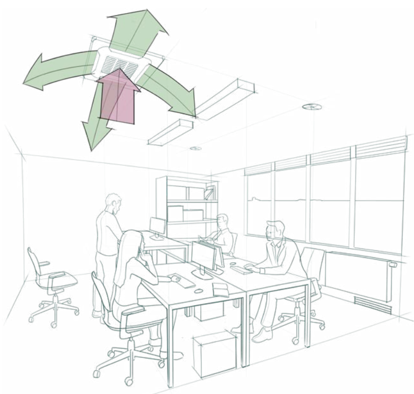
Figure 37
Displacement ventilation (bottom): illustration of displacement ventilation (Javed et al., 2021)

Ventilation Airflows

A simplified overview is provided for typical ventilation methods used in offices, how they work, and what kind of airflow they create.

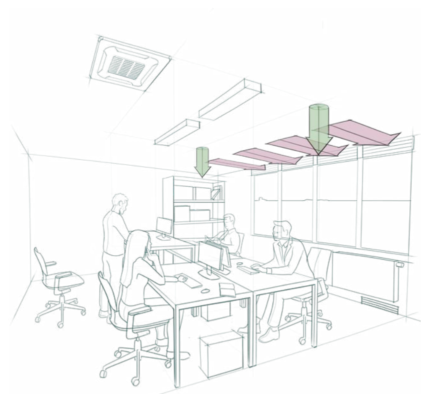
Mechanical

Mixing air HVAC (Cassette)



A system mounted to the ceiling or wall conditions the air, either heating or cooling, and supplied back into the environment at a velocity to reach far into the room, inducing turbulent mixing.

Positive pressure



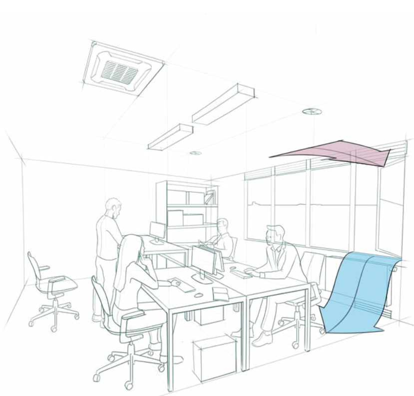
A fanned system that supplies fresh air through diffuser vents and expel air through façade openings such as trickle vents. Mixes air turbulently in the room.

Displacement

A system that removes stale air in stratified areas near the ceiling, which uses negative pressure to draw in colder air through façade openings. Induces a convective flow upwards.

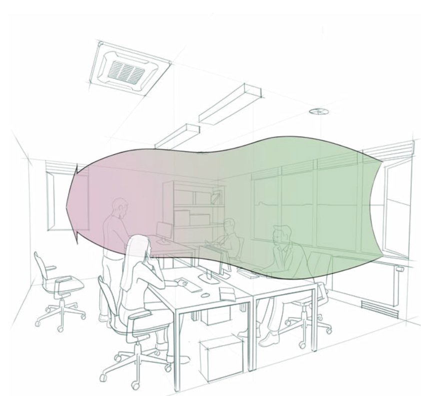
Natural

Single-sided ventilation



Single sided ventilation uses one or more openings on one façade. A pumping activity induced by wind turbulence creates low levels of air inflow and outflow.

Cross-ventilation



Cross ventilation is wind driven, where it uses the pressure difference of windward and leeward façades to create a draft indoors. More effective than single-sided ventilation.

2.5.2 - Volumetric Flow Rate Requirements

An essential question for to the efficiency of the Personal Air Filter is how much air needs to be filtered. An attempt is made to quantify this based on recommendations from literature and the Federation of Europe Heating, Ventilation, and Airconditioning (REHVA). The requirements for volumetric flow rate[11] and proximity to the user are discussed.

[11]
Volumetric flow rate is the volume of fluid which passes per unit time as described the formula:

$$Q = vA$$

Q = volumetric flow rate
v = flow velocity v
A = cross-sectional vector area

Air Changes Per Hour (ACH)

The requirements should be based on the context that is designed for. A larger room will need an air purifier with a higher volumetric flow rate.

According to Allen et al. to achieve a corona-safe working environment, 5 Air Changes per Hour[12] (ACH) is required (2021). The REHVA also recommends that 5 ACH is for filtering aerosols (REHVA, 2020b), whereas the current minimal standard in the Netherlands is 2 ACH (Bouwbesluit, 2022). It can be reasoned that the device must at least produce a minimum of 3 ACH, which is equivalent to roughly 50 m^3/h. Calculations were made based on room volume and desired ACH, which can be seen in Appendix J.

[12]
ACH is the number of times that the total air volume in a room or space is completely removed.

Rules and Regulations

Another method of determining the required ventilation rate is to follow guidelines as described in EN 16798-1. When considering these guidelines, ventilation requirements in an office typically needs to be 10-15 L/s per person (36 – 54 m^3/h) (Kurnitski et al., 2021). This considers the overall ventilation system, and not the Personal Air Filter, which is also influenced by the proximity of the user.

Proximity & Dilution

The goal is to create a device that filters respirated air close to the user. The closer the device is to the user, the more effective it will be. The viral density is proportional to the inverse square law of distance from the infected host (Yamamoto, 2020). Therefore, less volumetric flow rate is necessary the closer the device is to the user. A volumetric flow rate of 50 m^3/h should suffice for 1 person; however, this does not consider the proximity effect to the infected host. If results show it is too little, the volumetric flow rate will need to be increased.

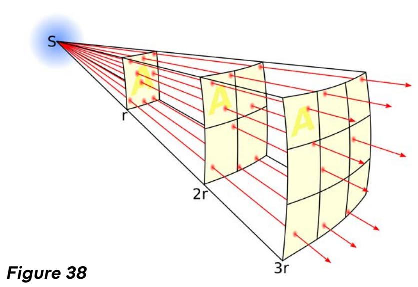


Figure 38
Inverse Square Law

Limitations

Literature suggests it is arbitrary to quantify it in ACH, as the plume propagation (such as sneezing, coughing, or talking) and quanta generation rate are not taken into account (Buonanno et al., 2020). Nonetheless, an educated guess is taken as a start to have a measurable requirement. Hospitals for example also use ACH to calculate the ventilation requirements (ANSI/ASHRAE/ASHE Standard 170-2021: Ventilation of Health Care Facilities, 2021).

2.5.3 - Ventilation Methods

A range of filtering methods are evaluated together with the client to select the most appropriate one for this application. The working principle of chosen method is further explained to gain insight in the components necessary for the Personal Air Filter. The state of the art of fans are researched to select the most appropriate type. The state of the art helps evaluate the feasibility of future concepts.

Air Purification Methods

First, different methods for air filtering are analyzed and evaluated against relevant criteria for the Personal Air Filter; viruses & pollutants, safety, level of noise, cost, and energy use.

Air purification removes particles from an air stream through a variety of methods. Common methods used are filtration, adsorption, ozonation, and photocatalysis (Ribot et al., 2006). These methods are evaluated for performance against viruses and other pollutants, safety, level of noise and cost, and energy use. For the full analysis, consult Appendix K.

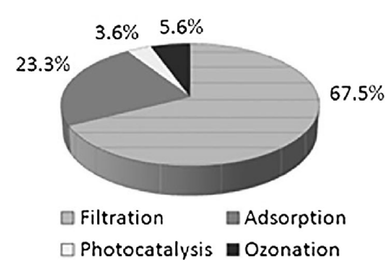


Figure 39
The market devices based on adsorption, filtration, photocatalysis and ozonation for improving indoor air quality (Ribot et al., 2006)

From the analysis, it is evident that HEPA filters are most suitable for filtering viruses and pollutants, as well as being the safest option. The Centers for Disease Control and Prevention encourages using HEPA filters as opposed to other air purification methods as it is most suitable solution for reducing the risk of transmission of Covid-19 (CDC, 2021).

It is however evident that no single method suffices in all criteria, especially noise levels of mechanical ventilation with HEPA filters and maintenance costs are high. A combination of purification technologies may be more suitable (Luengas et al., 2015). This is however associated with higher overall costs in initial price and maintenance. Therefore, Euromate has a clear preference for using only HEPA filters (personal communication, 2022). The downside compared to the other methods is high noise levels and maintenance cost due to frequent filter replacement.

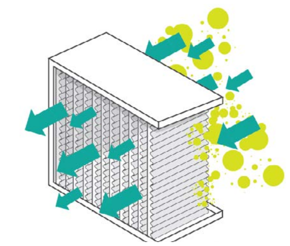


Figure 40
Visualization of HEPA filter filtering particulate matter (Difference Between a HEPA and ULPA Filter | HEPA vs ULPA Filter, n.d.)

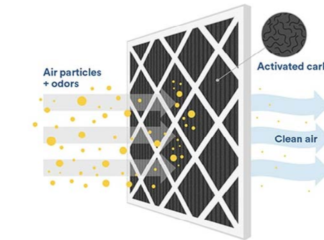


Figure 41
Visualizing how a carbon filter works (How Does a Carbon Filter Work?, n.d.)

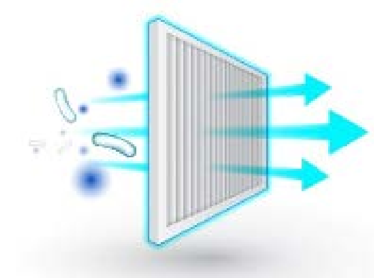


Figure 42
Visualizing how a ozonation works

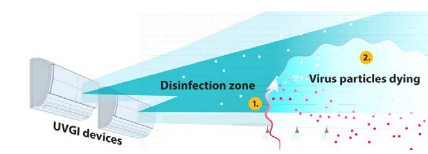


Figure 43
Visualization of upper-room UVGI for air purification (photocatalysis)

How does a HEPA air purifier work?

The working principle of an air purifier can be explained using the visual in figure 44. A fan within an enclosure produces negative pressure drawing in air through the filters. Most Air Purifiers use a pre-filter, such as a MERV 9 or a simple mesh to catch large particles like dust, dirt, and hair. An activated carbon filter is used to remove volatile organic compounds (VOCs) before the air is filtered by the HEPA filter. Fresh air is then exhausted through openings on the outside of the device. The performance is related to the effectiveness of the filters, the type of fan used, and location of the exhaust vents.

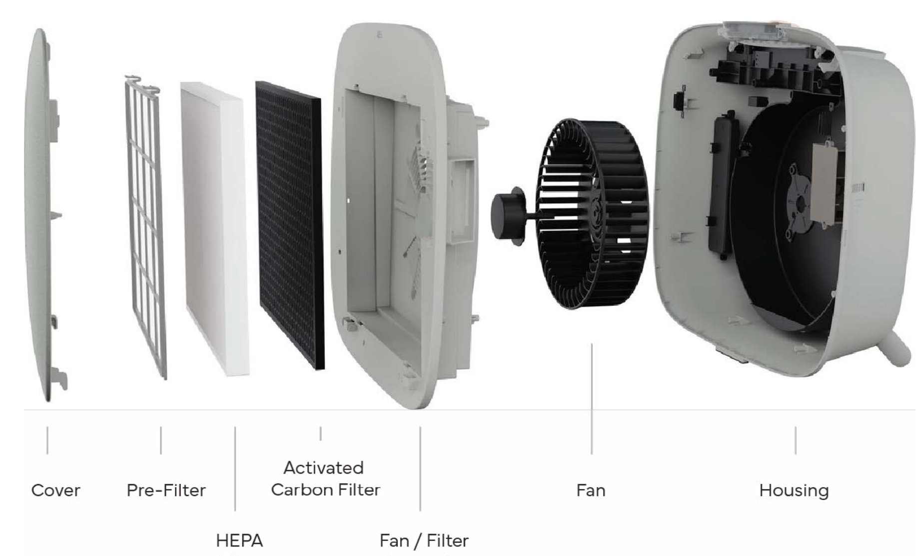


Figure 44
Components of AEG AX7 Air Purifier

2.5.4 - Fans

Understanding the current state of the art for fan technology will help select the right components for the Personal Air Filter. In this chapter, axial and centrifugal fans are compared and contrasted in relation to air purification.

Axial vs. Centrifugal

There are two basic fan categories, namely axial-flow and centrifugal fans (figure 45). Both types have benefits and disadvantage related to the application for air purifying systems. A comparison can be found in Appendix L.

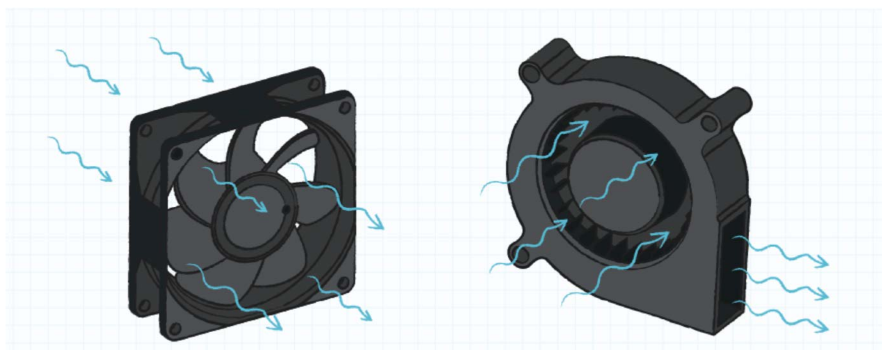


Figure 45
Axial fan (left), centrifugal fan (right) (Smoot, n.d.)

Overall, centrifugal fans are better applicable to air purifiers using a HEPA filter as they can operate against a high resistance (Bloch & Soares, 1998). "These fans are applied in building and equipment ventilation, hot-gas recirculation, dusthandling systems, and furnace and boiler forced draft/induced draft services" (Bloch & Soares, 1998). Axial fans are not applicable for local exhaust ventilation since it does not deliver enough suction to draw air (4-Fans, 2016). On the downside, centrifugal fans produce more noise than axial fans, which will be further discussed.

Noise

Noise will be produced by any fan but is influenced by a range of factors such as the placement in a system, density of the components, volumetric flow rate, size of the fan, the bearings used, and more (Smoot, n.d.). First, the audible noise can be minimized by fan placement and using isolation. For example, the further the fan is placed away from the user the lower the audible sound. Also, resonance should be avoided as it amplifies noise. Furthermore, the higher the volumetric flow rate, the more noise is produced. This can be minimized by using larger fans, as the volumetric flow rate is proportional to RPM (Appendix M) (Powell, 2015).

Radial, Backward-Inclined, Forward-Inclined

There are subtle variations in blade shapes available for a variety of purposes. Each have benefits regarding efficiency, static pressure (SP), brake horsepower (BHP), noise and more.

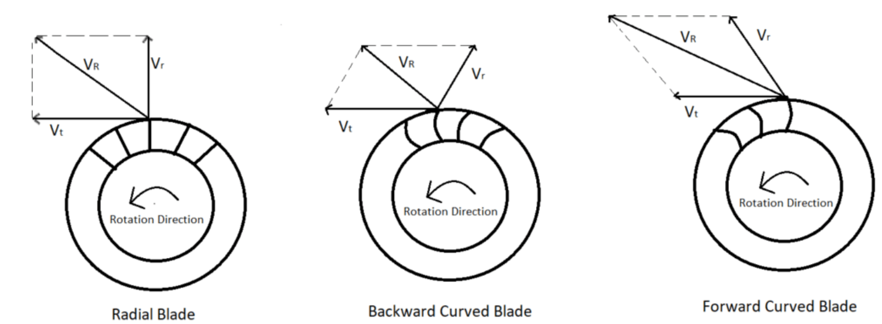


Figure 46
Radial blades, backward curved blade, forward curved blade for centrifugal fans (Types of Centrifugal Fans, 2021)

The most suitable centrifugal blade type is the forward-inclined blade. These are positioned in the same direction as the rotation of the fan. These fans are quieter than the other types but do have a lower pressure. As a result, these fans are typically only used for air filtration systems. The AEG AX-7 air purifier used in the user experience tests uses a forward inclined centrifugal fan for example.

2.5.5 - Ventilation & Purifying Key Insights

RO5: How do air purifiers work, and what method is most effective for filtering viruses?

Ventilation Methods

- Three main strategies for ventilation; recircling ventilation, mixing ventilation, and displacement ventilation.
- Opportunity area to retrofit the Personal Air Filter in offices using mixing and recircling ventilation as these are counterproductive in reducing airborne transmissive diseases.
- Working principles of displacement ventilation may be most suitable for the personal air filter.
- Existing ventilation methods will induce airflows that can interfere with the working of the Personal Air Filter and should be tested with a prototype and/or CFD simulations.

Volumetric Flow Rate Requirements

- Product needs a volumetric flow rate of 100 m3/h per person.

Air Purifying

- Common methods used are filtration, adsorption, ozonation, and photocatalysis.
- HEPA filters are most suitable for filtering viruses and pollutants for this case, as well as being the safest option.
- Euromate has a clear preference for using only HEPA filters (personal communication, 2022).
- Downside to using HEPA filters is high noise levels and maintenance cost due to frequent filter replacement.

Fans

- Centrifugal fans are better suited than axial fans for a HEPA filter system due to the better performance with high resistance.
- Centrifugal fans are noisier than axial fans but can be reduced in the design through sound insulation, placement, minimizing resonance, and using larger fans at lower RPM.
- Forward-inclined centrifugal fans best suited for the Personal Air Filter.

2.6 - Conclusion

The relevant findings in the context, product use and performance from the 'discover' phase are concluded on in this chapter in two sections; the context and product use & performance.

2.6.1 - Context

The challenge lies in designing a device that is focused on effectively and efficiently filtering aerosols, while providing an attractive and desirable user experience. To design a desirable product, the Personal Air Filter should fit within the intended context. Figure 47 shows a mental map of all relevant context factors that influence the product requirements.

The device will be designed to integrate in a variety of offices and ranging desk setups. The use scenario is focused on seated desk areas with employees sitting opposing each other to limit the scope and to increase chances of creating a proven working product. Furthermore, besides improving air quality, the device could also improve the overall well-being of the user through lighting and/or local heating.

As purpose designed air purifiers for offices and particularly the desk area is rare, there is a viable market opportunity for new product development. The product can be retrofitted in rooms using mixing and recirculating ventilation strategies as these "provide the optimum conditions for rapid disease spread in high occupancy buildings" (Lipinski et al., 2020). Working principles from displacement ventilation can be utilized as the non-turbulent air flow is better suited in combating virus transmission.

The aim of the Personal Air Filter is to reduce concentration of aerosols as to reduce the risk of infection of airborne transmissive diseases. An assumption is made that 100 m3/h per person should suffice in filtering aerosols effectively. The device should also take into account context factors, such as the product placement relative to the propagation of aerosols, however this may be challenging to quantify. During the development phase a range volumetric flow rates should be explored and validated, as well as the implications of other ventilation systems.

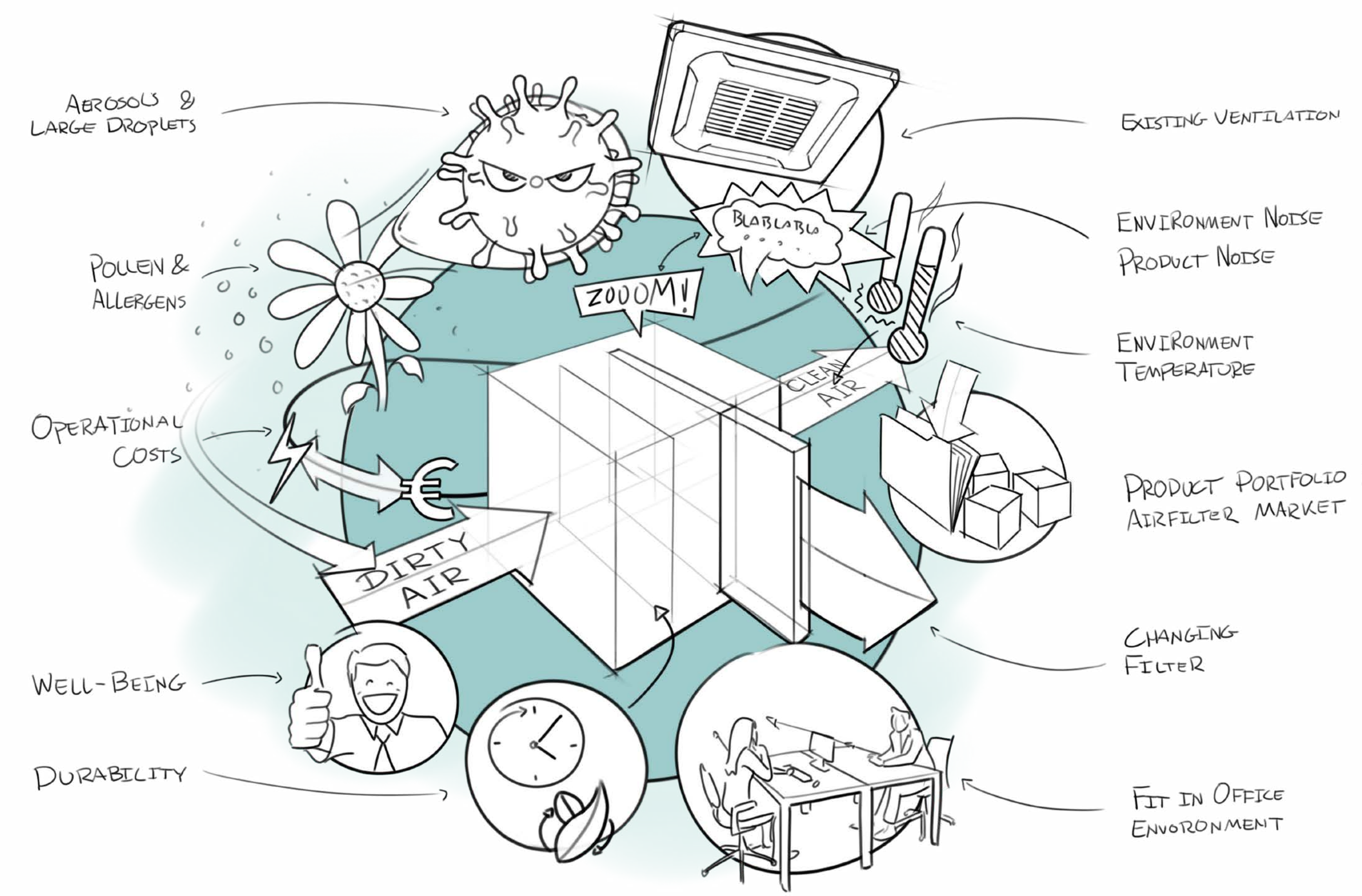


Figure 47
Mental map of all relevant context factors for the Personal Air Filter. Source: Author

2.6.2- Product Use & Performance

The most important user aspect of the Personal Air Filter is the noise it will produce. A loud device will result in a bad product experience and consequently inefficiency of the employee in the office. Components will have to be selected to achieve 50 m3/h per person without exceeding audible noise of 45 dB. Furthermore, the product architecture will also impact the noise produced such as the size of the fan, the materials used for sound insulation, and if there is any resonance. Ideally, an oversized centrifugal fan should be used that runs at lower RPM. The development phase should focus a validating and improving the level of noise that is produced by the product.

The HEPA filter is chosen together with Euromate as the most appropriate method for purifying air for the purpose of the Personal Air Filter. On the downside, it is evident that these filters need to be periodically replaced but may not always be clear to the user. A product/service system should be designed that nudges the user to change the filter when necessary.

Furthermore, the thermal comfort will also influence the well-being of the user. The 'wind-chill effect' will need to be minimized to ensure good thermal comfort. Furthermore, there may be a possibility to integrate local heating, allowing users to exert control over local temperature. In theory, this should increase user satisfaction and working efficiency.

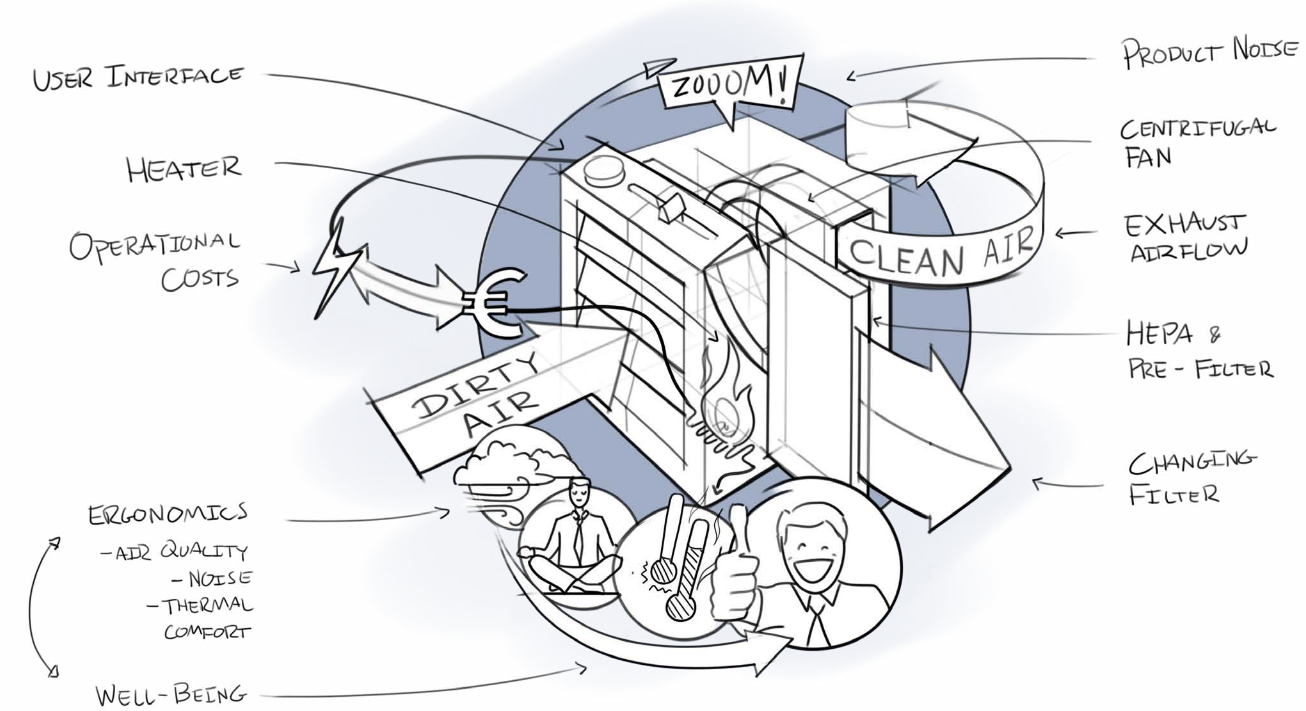


Figure 48

Mental map of product use and performance factors relevant to the Personal Air Filter. Source: Author

CHAPTER THREE

DEFINE

The context and air filter analysis have highlighted several problem themes and opportunity areas. A thorough understanding of the current context setting, ergonomic needs of the user, and available technologies and limitations have led to a redefinition of the design vision, as well as specified design drivers that will be used for the design development of the product.

3

"The challenge is to develop a Personal Air Filter ***for workspaces in offices*** *that* ***reduces aerosols to an acceptable level*** *to prevent transmissions of airborne transmissive diseases between desks. The* ***trade-off between product performance and user experience*** *should be optimized to create a feasible, viable, and desirable device for all stakeholders involved.*

Specifically, the Personal Air Filter is ***easy to implement and fits in the office context****, while considering the* ***optimal placement for efficiently filtering*** *viruses, pollen and other allergens. The* ***noise of the device is minimized*** *to create a comfortable, desirable, and safe work experience."*

3.1 – Vision

Throughout the analysis, extensive understanding of the existing process, user requirements, the technologies at hand, their limitations, and the current market situation. This valuable knowledge served as the foundation for shaping a more precise design statement and determining the key factors driving the design, encompassing the fundamental functionalities and features that the product must encompass. The revised vision can been seen on the previous page.

The initial (old) vision of the project was:

"The trade-off between user experience and product performance should be optimized to create a feasible and desirable device.

The Personal Air Filter must work with existing ventilation systems and should be non-intrusive to implement in the office, ultimately increasing air quality, reducing pollen, and viruses"

3.2 - Design Drivers

The design drivers are determining factors that shape the design of a product or system, encompassing its performance, user experience, versatility, and costs. In this project, the design drivers were determined after a comprehensive analysis of user needs, technological limitations, and other elements that could impact the product's success. By following the design drivers, informed decisions can be made to develop a product that fulfills critical requirements and achieves the desired outcomes. This chapter examines these design drivers.

3.2.1 - Product Performance

The performance design drivers for the device aim to reduce the risk of infection from airborne transmissive diseases. To achieve this, the device **must produce a volumetric flow rate of 50m3/h per person** to minimize the concentration of aerosols in the air. Additionally, in consultation with Euromate the device **must use a HEPA filter** to filter out 99.95% of viruses and allergens and deliver cleaned air back to the environment.

In order to optimize the device's performance, it is **required to consider breath propagation, thermal plumes, and air stratification in the room** where the device is to be placed. Ideally, the device **should be positioned within 0.2 meters in front and directly above the user**. Furthermore, it **should have the largest capture area possible** while being as close to the user as possible to increase its efficiency.

As the the presence of people in the office and activities taken place over time is variable, the air filter could adjust the CADR accordingly to optimize energy use and necessity for producing noise. For this, **smart sensors and connectivity between multiple Personal Air Filters** can optimize the balance between performance and efficiency.

3.2.2 - User Experience

These design drivers prioritize user experience and ease of use to create a device that is user-friendly, efficient, and effective at improving indoor air quality without causing any discomfort or disruption to the user.

Firstly, the device **must produce no more than an audible 45 dB (at 100% CADR when measured from the user)**, ensuring that it operates quietly and without disruption. Additionally, the device **must not cause a draft of more than 0.2m/s in the livable area of the user**, with a **maximum draft temperature change of 1°C**, to maintain comfort and minimize discomfort.

In terms of the HEPA filter, it **must be changeable and accessible to the user without the need for any tools**, while an **inexperienced or unfamiliar user should be able to replace the filter in one minute**. This ensures that users can easily maintain the device and keep it functioning at peak efficiency.

Furthermore, the device **must enable adjustability of product settings through an interface**. This includes allowing for the **adjustment of ventilation capacity from 0% (off) and 10% of the total capacity up to 100% of total capacity**. There should also be at least one additional setting in between, with more than 10% capacity difference, as outlined in the NEN 1087 standard.

3.2.3 - Versatility

Due to the changing needs of modern office environments it is important to create a device that is adaptable and versatile to ensure widespread adoption and long-term success.

The device **should be compatible with a range of desk setups, such as a 1x2 and 2x2 rectangular desk layout** as previously described in the context analysis. This ensures that the device can fit seamlessly into typical office environments of today and tomorrow. In addition, the device **should appeal to future office trends such as the feeling of comfort and home, and a place to meet**. This ensures that the device aligns with the changing needs and preferences of modern office spaces, providing a comfortable and welcoming environment for workers.

Furthermore, the device **should be compatible with environments that use mixing and recirculating ventilation** to ensure that it can be used in a wide range of settings. This enables the device to be adaptable to different office configurations and ventilation systems, further increasing its versatility.

Finally, the use of a **PaaS model could be applied to the filter system in the future**, allowing for greater flexibility and scalability in terms of maintenance and updates. This enables the device to be future-proof and ensures that it can continue to meet the evolving needs of office environments.

3.2.4 - Cost

Cost is a significant design driver for the Personal Air Filter. In order to be successful in the market, the product must be priced competitively and offer good value for money. To determine an appropriate price point for the device, a market analysis was conducted. During the analysis, it was found that there are no current personal air filtering solutions on the market to compare to. However, existing air purifiers with similar Clean Air Delivery Rate (200m3/h) range in price from €150 to €250.

Taking this into consideration, it was determined that the personal air filtering solution **should have a cost price below €300** (depending on the functionality of the product). This pricing strategy ensures that the product remains competitive in the market, while also offering good value for money to the end user.

3.3 - Prioritization

Figure 49 shows an overview of the above-formulated design drivers. The main focus of the project is to find a solution that considers the trade-off between product performance and user experience. The versatility should also be considered to ensure the device can be implemented in a wide range of offices. To enable creative freedom in finding solutions, costs not focused on for the initial development phase of the project.

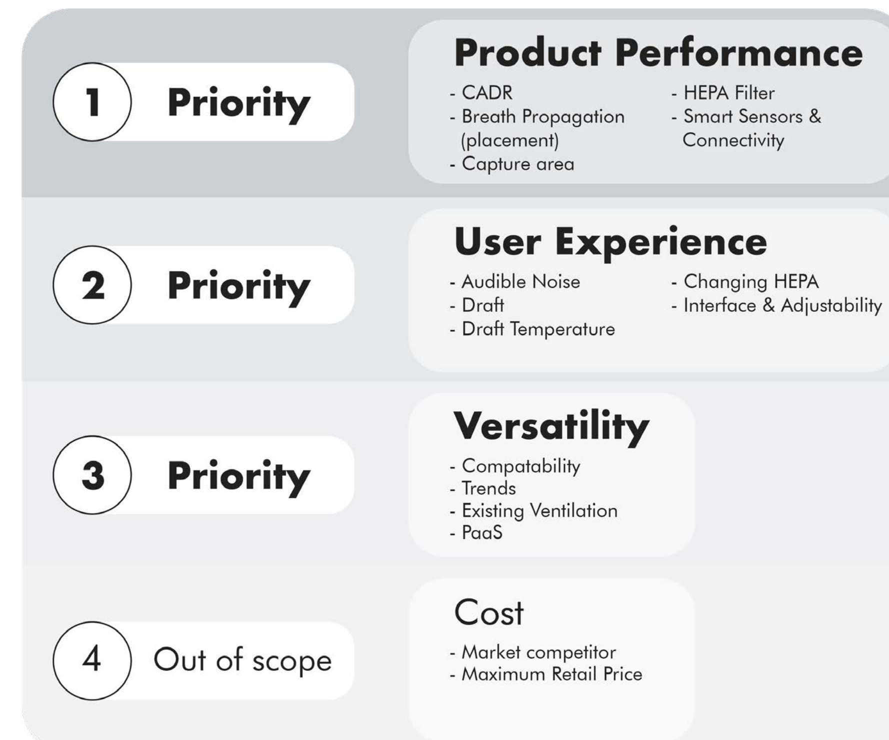


Figure 49
Overview and prioritisation of the formulated design drivers

3.4 - List of Requirements

The most important requirements are shown below. These are formatted in the MoSCoW method (**MUST**, **SHOULD**, **COULD**, Will Not) to prioritize according to importance. Furthermore, where possible the requirements are SMART (Specific, Measurable, Achievable, Relevant, and Time-Bound), and indicates how these requirements will be met and verified. A complete overview of the requirements can be found in Appendix B.

1. **MUST produce a volumetric flow rate of 50m3/h per person.**
2. **MUST produce no more than an audible 45 dB at 100% CADR when measured from the user.**
3. **MUST not cause a draft of more than 0.2m/s in the livable area of the user (with a maximum draft temperature change of 1°C).**
4. **MUST use a HEPA filter.**
5. **MUST filter, it must be changeable and accessible to the user without the need for any tools.**
6. **MUST consider breath propagation, thermal plumes, and air stratification in the room.**
7. **MUST enable adjustability of product settings through an interface (adjustment of ventilation capacity from 0% (off) and 10% of the total capacity up to 100% of total capacity).**
8. **SHOULD be compatible with a range of desk setups, such as a 1x2 and 2x2 rectangular desk layout.**
9. **SHOULD have the largest capture area possible.**
10. **SHOULD be compatible with environments that use mixing and recirculating ventilation.**
11. **SHOULD have a cost price below €300.**
12. **SHOULD be able to replace the HEPA filter in one minute by an inexperienced user.**
13. **SHOULD appeal to future office trends such as the feeling of comfort and home, and a place to meet.**
14. **COULD use smart sensors and connectivity between multiple Personal Air.**
15. **COULD implement a PaaS model to the filter system in the future.**

CHAPTER FOUR

DEVELOP

The development phase of the Personal Air Filter shows the initial ideation and conceptualization iterations. During this part of the report, the concept is transformed into a tangible product through detailed design, prototyping, testing, and refinement. Furthermore, concepts are tested evaluated through a range of tools and methods to make informed design decisions.

4

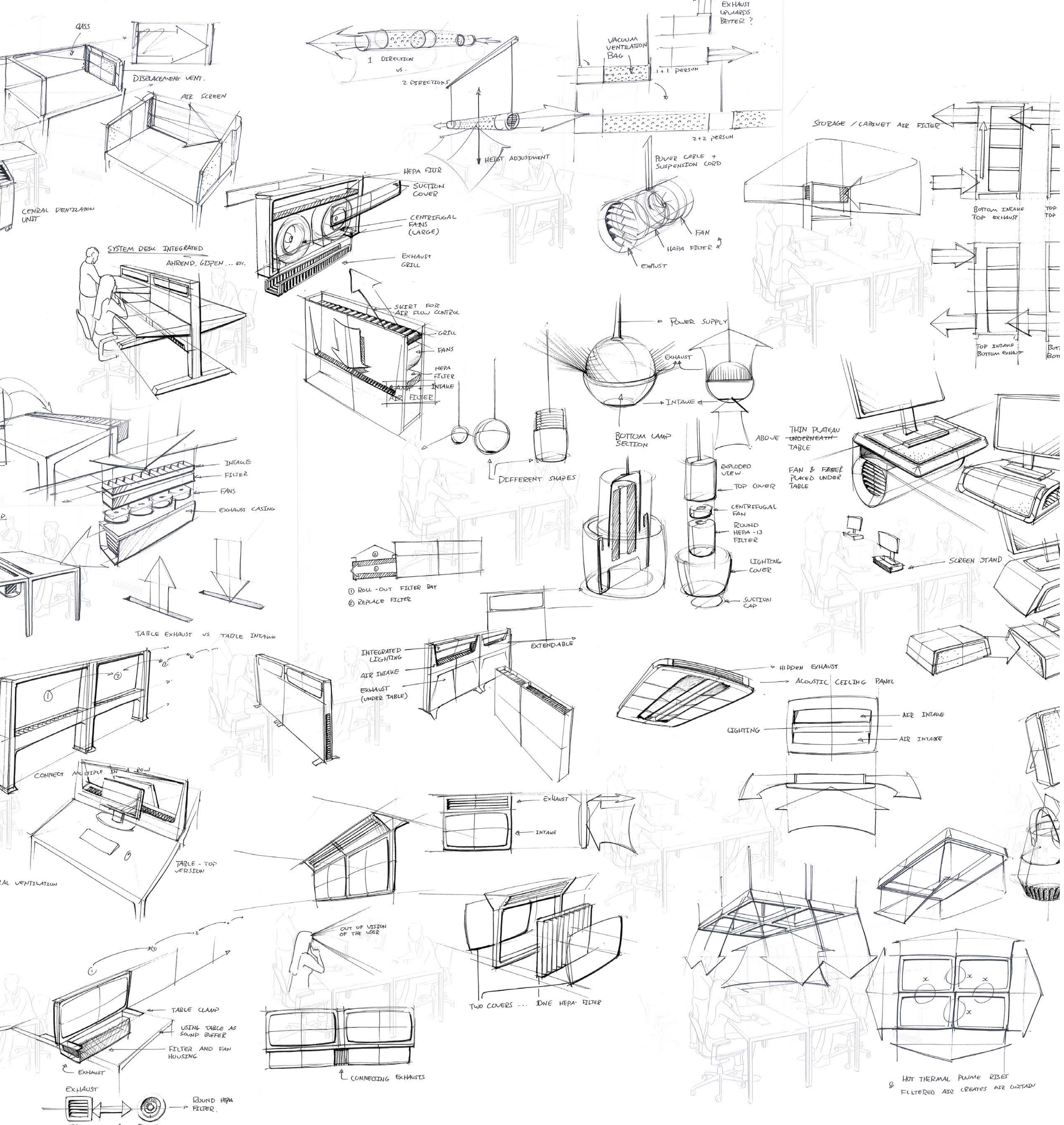


Figure 50

Initial placement ideation for the Personal Air Filter

4.1 - Ideation

Since the projects focus is design oriented, Design Thinking was employed as a methodology to investigate prospective solutions. There were various iteration stages with diverging and converging where stakeholders were involved from the very beginning. Prototyping and testing were done in early stages to gain an understanding of the design task at hand. The Loughborough Design School iD cards (Evans, n.d.) proved to be an valuable aid in selecting the appropriate visualization techniques for each phase of the process.

4.1.1 - Placement Ideation

One of the most limiting factors for the Personal Air Filter is the placement within the working area of the office employee. A variety of idea sketches were brainstormed to consider both placement and product performance (large capture area, plume propagation). An overview of the first ideas can be found in figure 50.

Clustering

The ideas from the brainstorm were grouped and clustered as seen in figure 51. In the clustering process, four main categorized were identified: dividing wall, desk integrated, ceiling suspended, standalone unit. Each category has one image highlighted with variations of the idea surrounding it.

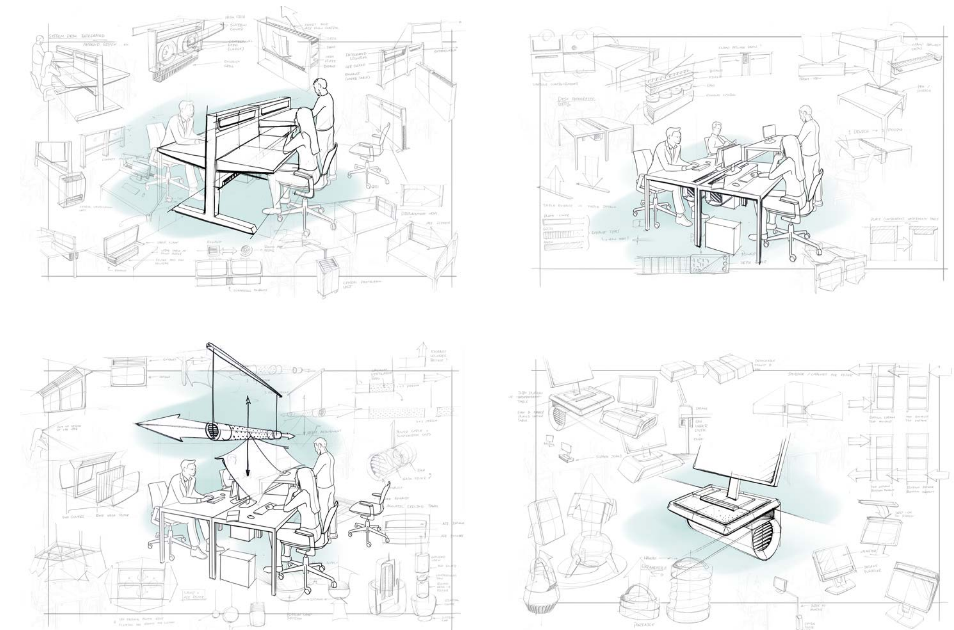


Figure 51

Clustering of ideation sketches for placement of Personal Air Filter in 4 categories: (1) Dividing Wall, (2) Desk Integrated, (3) Ceiling Suspended, (4) Standalone Unit

4.1.2 - Idea Visualisation

Sketch renderings were made for the 6 idea directions identified during the product ideation to present to Euromate (figures 52-57). The goal was to pinpoint viable and desirable directions to further develop into advanced concepts. For each sketch render, the imagined air flow of the intake and exhaust were drawn, as well as miscellaneous design considerations relevant to the concept. These were added to aid the discussion with the client.

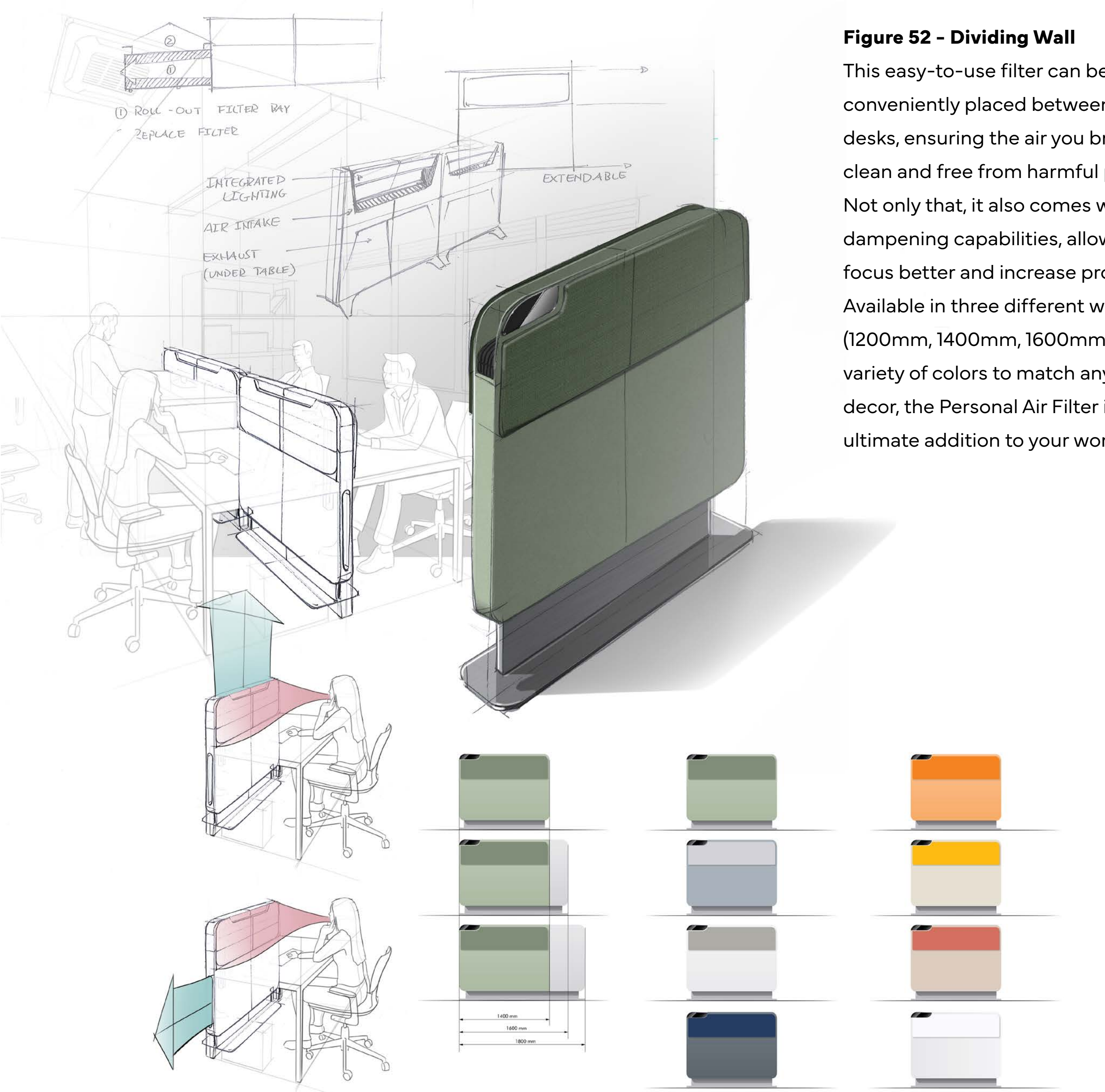


Figure 52 - Dividing Wall
This easy-to-use filter can be conveniently placed between office desks, ensuring the air you breathe is clean and free from harmful particles. Not only that, it also comes with sound-dampening capabilities, allowing you to focus better and increase productivity. Available in three different widths (1200mm, 1400mm, 1600mm) and a variety of colors to match any office decor, the Personal Air Filter is the ultimate addition to your workplace.

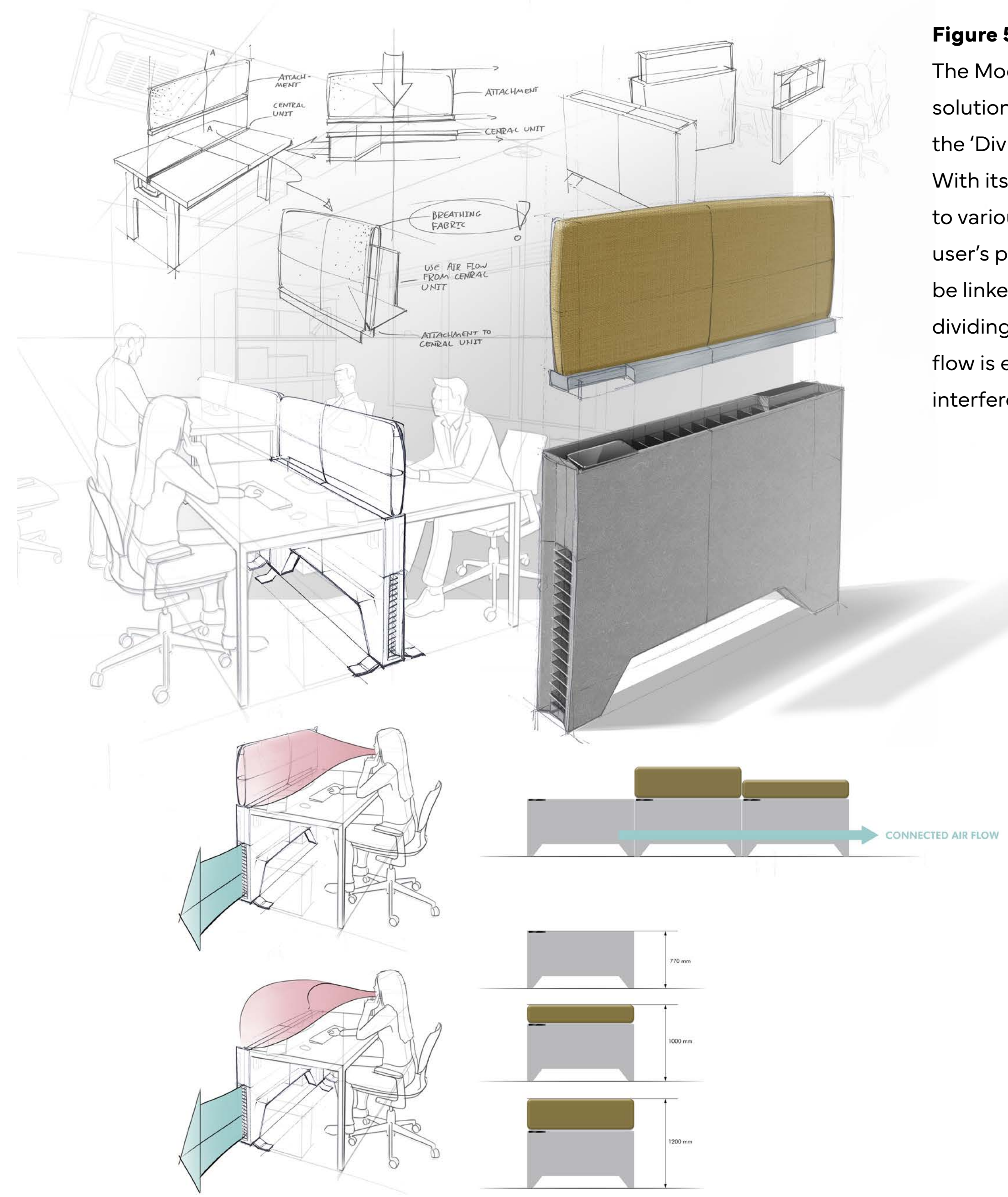


Figure 53 - Modular Dividing Wall
The Modular Dividing Wall is a versatile solution that provides all the benefits of the 'Diving Wall' with added flexibility. With its modular top, it can be adjusted to various heights according to the user's preferences. The walls can also be linked together to create a larger dividing surface, while the exhaust flow is expelled sideways to prevent interference with the work area.

Figure 54 – Lamp Integrated
A solution that seamlessly integrates air filtration and lighting into one sleek design. The Lamp Filter filters the air within the immediate vicinity of your workspace without any noticeable noise or draft. Designed to blend seamlessly into your office décor, the Lamp Filter also functions as a pendant lamp, providing ample lighting for optimal work conditions.

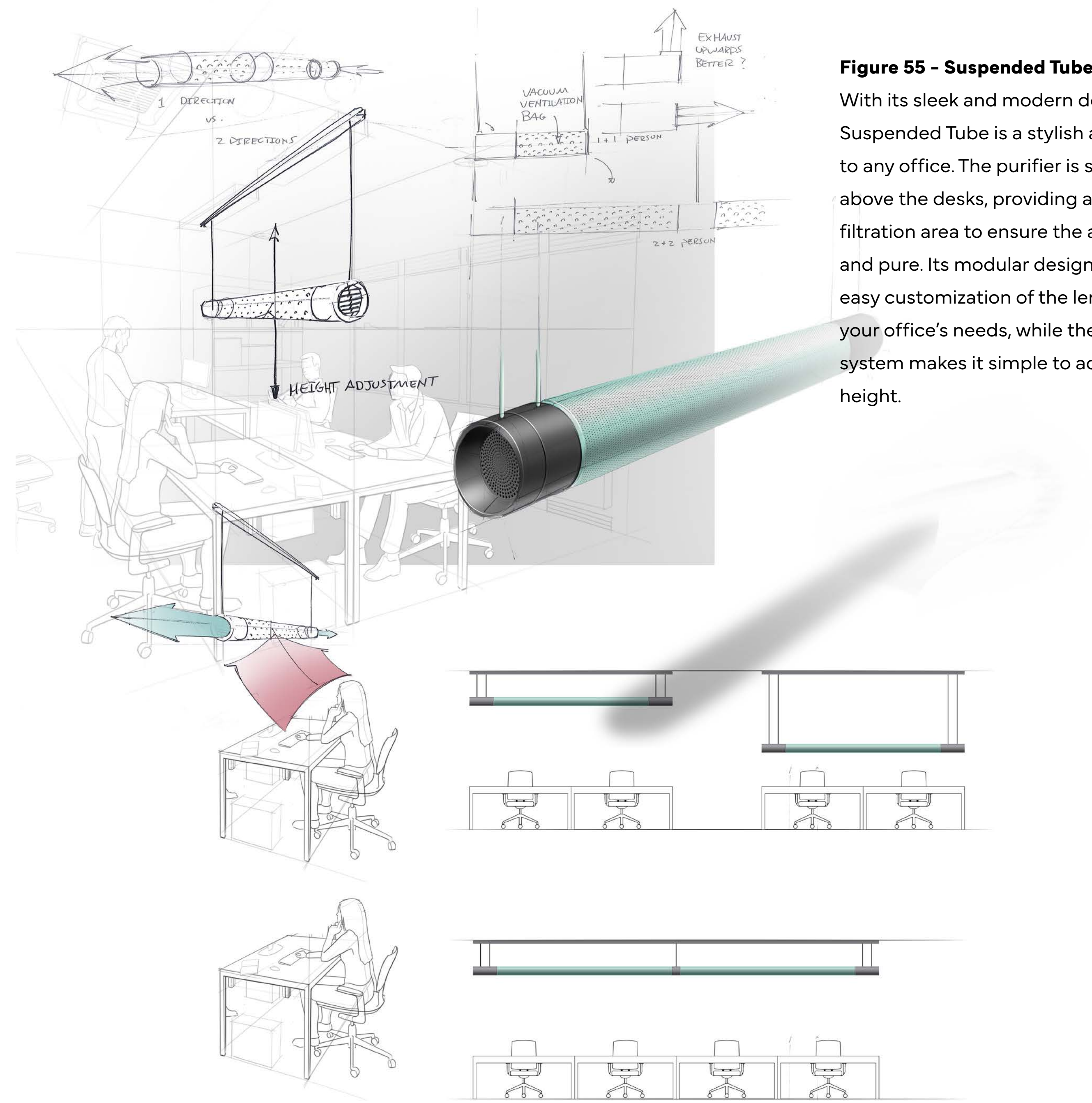


Figure 55 – Suspended Tube
With its sleek and modern design, the Suspended Tube is a stylish addition to any office. The purifier is suspended above the desks, providing a long filtration area to ensure the air is clean and pure. Its modular design allows for easy customization of the length to fit your office's needs, while the pulley system makes it simple to adjust the height.

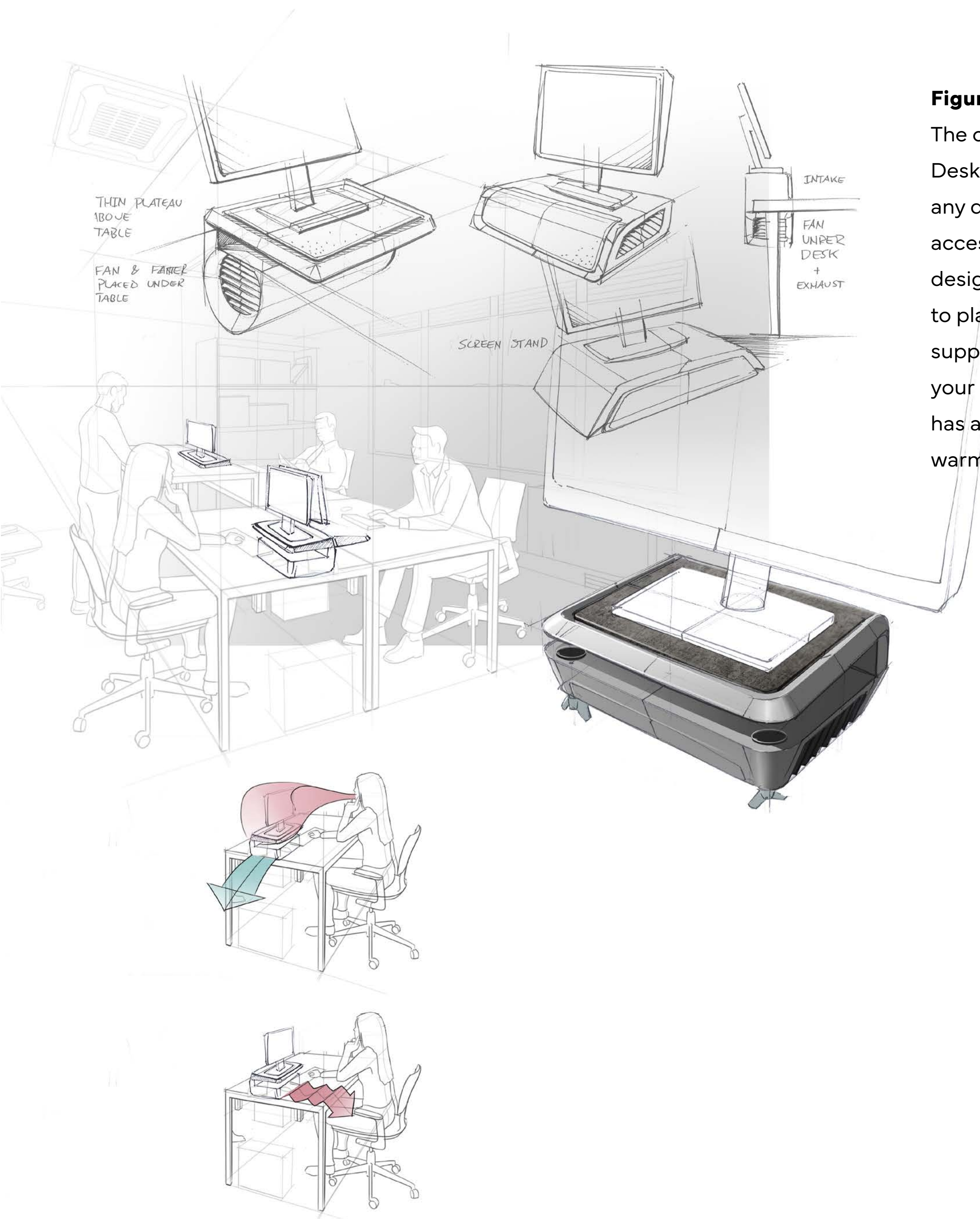


Figure 56 - Desk Clamp

The compact and slim design of the Desk Clamp allows it to fit seamlessly on any desk surface, making it the perfect accessory for your workspace. The sleek design also makes it a perfect surface to place your monitor or other office supplies, ensuring you make the most of your desk space. The Desk Clamp also has an optional heater that keeps you warm and cozy during cold winter days.

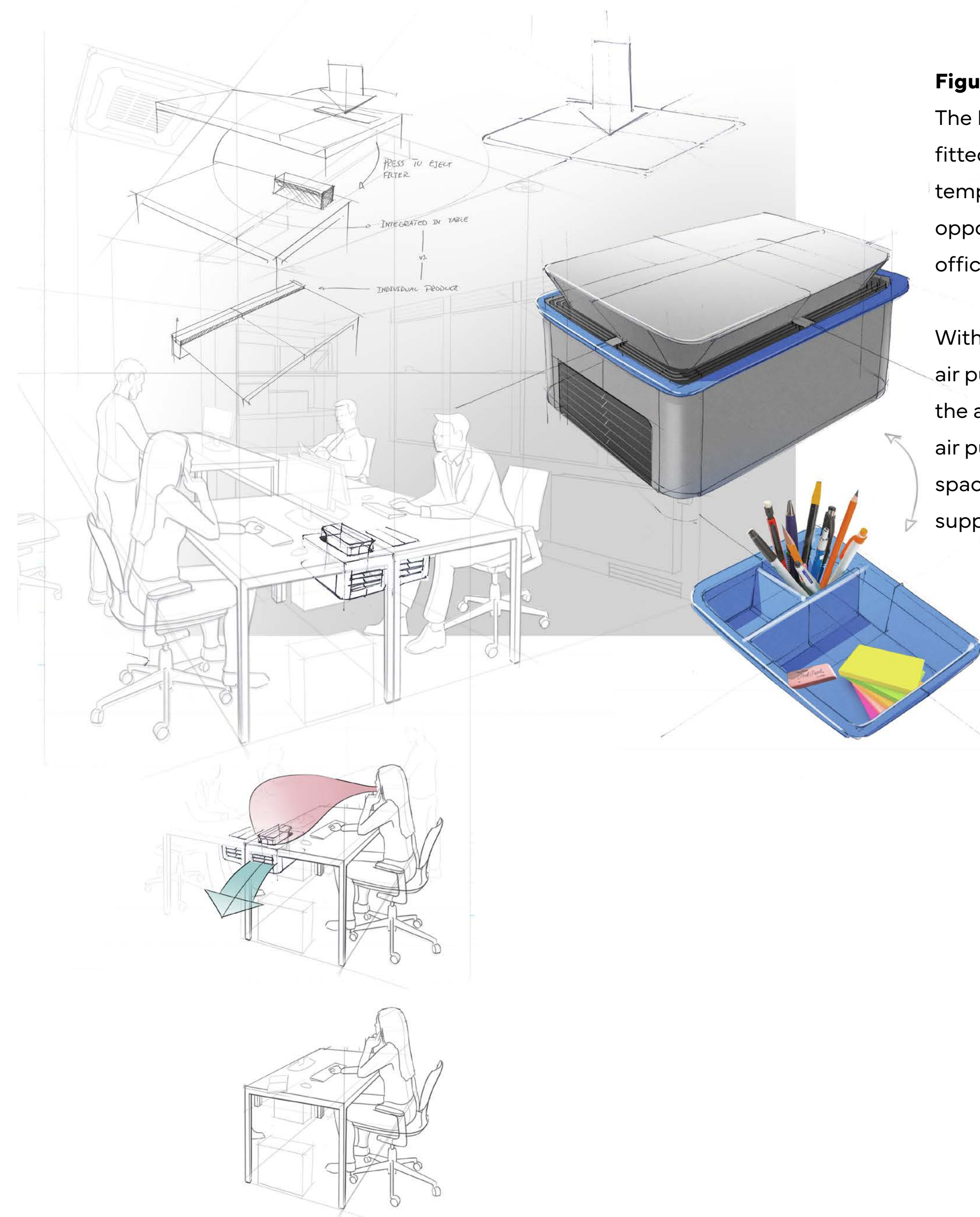


Figure 57 - Desk Integrated

The Desk Integrated air purifier can be fitted to any desk with a simple milling template. This allows for business opportunities to work together with office furniture manufacturers.

With a single press, the Desk Integrated air purifier ejects and starts filtering the air. Not interested in including the air purifier in your desk. No worries, the space can be used to fit your office supplies.

4.1.3 - Conclusion

These six ideas were evaluated with FLEX/design and Euromate for potential. The Plus/Minus/Interesting (PMI) method was used to summarize the discussion found in Appendix N.

In consensus with Euromate and FLEX/design, the two design directions shown in figure 58 were identified to have the most potential. The weighted criteria method (using the design drivers in chapter 3) was used to evaluate the ideas against each other (Appendix O).

Figure 58
Design directions with the most potential

The aesthetic quality of most proposed solutions appealed to the client, however there were doubts about the product performance in filtering the breath of the user. These two concepts had the best chance to work with some alterations according to the experts at Euromate. For example, the suspended lamp was suggested to have a large capture area for the inlet to improve efficiency.

It was concluded that to make an informed decision between the two design directions, a study to understand the placement of the Personal Air Filter relative to the user's breath is necessary.

4.2 - Optimizing Product Performance

An experiment was set up to test how the placement of the air purifier affects the performance of filtering the user's breath. The goal is to visualize and quantify the effectiveness of the air purifier in different scenarios. Furthermore, the draught levels were also measured to see whether a wind-chill effect would occur in the livable space of the user. This information can then be used to evaluate the chosen concept directions based on performance. The full experiment, with test setup, methodology, results, and discussion can be found in Appendix P.

Figure 59
Visualization of proposed test setup

4.2.1 - Test Findings

No concrete conclusions for deciding a concept direction can be drawn from the tests. The uncertainty of the results as argued in the discussion in Appendix Q are too big to make a crucial design decision. Ultimately, a better study and advice from experts is needed to understand and make a supported decision for the concept direction. However, there are learnings that can be drawn from the tests.

Coanda Effect

First, the Coanda effect (figure 60) can be made use of to elongate the reach of the air purifier. Comparing the air velocity measurements in between scenarios 2 and 2.1 shows how the dividing wall induces the Coanda effect by increasing airflow lower than the filter. Making use of this phenomenon can improve the efficiency of the air purifier.

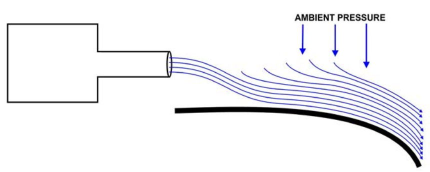


Figure 60

Coanda effect "the tendency of a fluid jet to get adhered to a nearby surface and remaining adhered. If the surface is curved, the fluid stream curves away from its initial direction and follows the surface"

Air Flow Resistance

Furthermore, the scenarios without the exhaust pipe were much more efficient than the scenarios with. This is due to the drag that is induced by the walls of the exhaust pipe and the tube. The drag equation shown in figure 61 indicates that the larger the surface area, the more drag. Therefore, the Personal Air Filter should avoid channeling air through long tubes.

$$F_d = \frac{1}{2}\rho u^2 C_d A$$

Where

- F_d is the drag force, which is by definition the force component in the direction of the flow velocity
- ρ is the mass density of the fluid
- u is the flow velocity relative to the object
- A is the reference area
- C_d is the drag coefficient

Figure 61

Drag force equation for liquids

The scenarios without the exhaust pipe showed relatively fast air velocities (0.3m/s) in the proximity of the air purifier. The exhaust air is pulling the 'dirty' air along with it, thereby preventing it from going in the air filter. The air intake and air exhaust should therefore be significantly separated in the design proposal to not interfere with each other.

Prototype vs. Product Efficiency

Last, it is evident that the AEG AX7 air purifier was much more effective than the prototype. Factors such as better air sealing (better negative pressure build up), and a more efficient fans (centrifugal vs. axial) are reasons for this.

4.3 - CFD Analysis

As there was no concrete outcome for the best placement of the air purifier, a CFD analysis was executed using Solidworks Flow Simulation. A model for the test setup seen in figure 62 was made in which a wide range of factors were tested and compared to find the optimal solution. For the full report with results, see Appendix S. The most promising results from the dividing wall and hanging lamp are compared to make a design direction decision. Aerodynamic expert Gijsbert van Marrewijk validated the methodology and findings to ensure no mistakes were made.

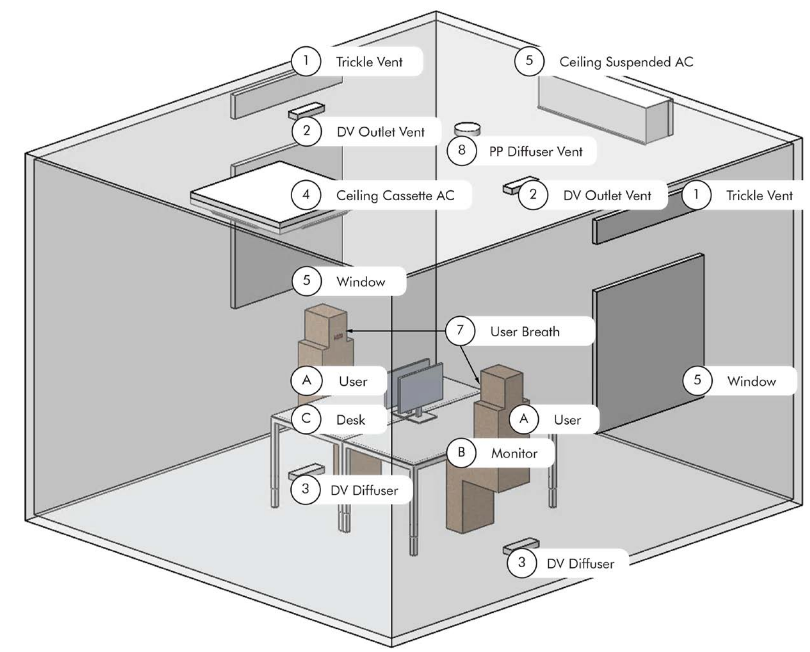


Figure 62

Visualization of proposed test setup

4.3.1 - CFD Findings

To compare the results, cut plots (cross-sectional view) were taken in the symmetric center of the room. Three different plots are compared. The air velocity and path of user breath shows the plume propagation of the user when breathing at a normal rate. The air velocity cut plot shows the air speed at any point in the 2-dimensional space. The draft temperature cut plot shows what the predicted feeling temperature will be. The results shown use a volumetric flow rate of 200 m^3/h (100 m^3/h per person), as opposed to the original suggested 50 m^3/h per person .

Dividing Wall

Figure 63 shows the propagation of the user's breath to spread turbulently through the air with time (5 minutes total). It shows no 'dirty' air going directly towards the air purifier. The air velocity cut plot shows the air velocity is ca. 1m/s directly at the exhaust and rotates downwards back towards the exhaust at roughly 0.4m/s.

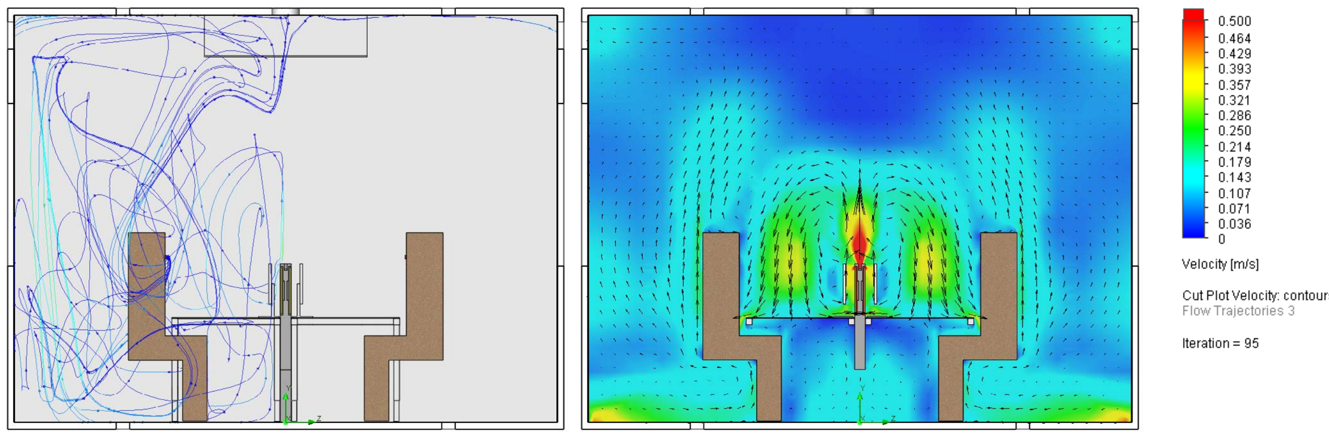


Figure 63
Dividing Wall: Air velocity and path of user breath (left), air velocity cut plot (right)

The draft temperature plot in figure 64 shows a draft temperature of -3°C in the livable space of the user. The draft temperature around the user, the monitors, and at the ceiling are between 2°C and 3°C above room temperature.

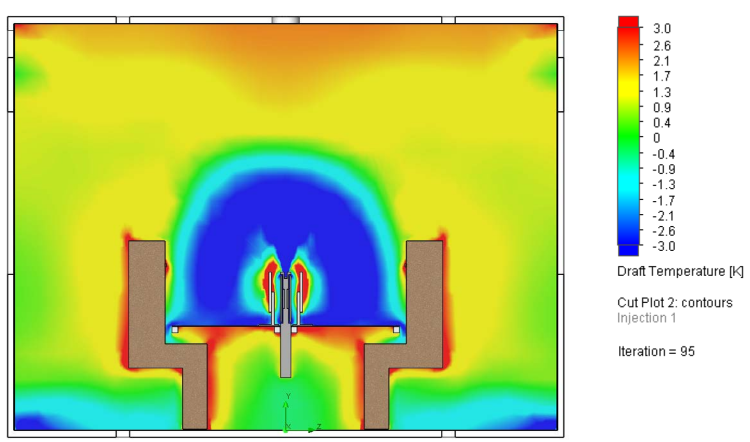


Figure 64
Dividing Wall: Draft temperature relative to environment temperature (20°C)

Hanging Lamp

Figure 65 shows the propagation of the user's breath to go directly in the air purifier. The air velocity of the breath accelerates to approximately 0.2m/s at the edge of the filter. The air velocity cut plot shows the air velocity is ca. 1m/s directly at the exhaust and rotates upwards in a circular motion towards the ceiling at 0.2m/s. The exhaust and intake velocities are clearly separated.

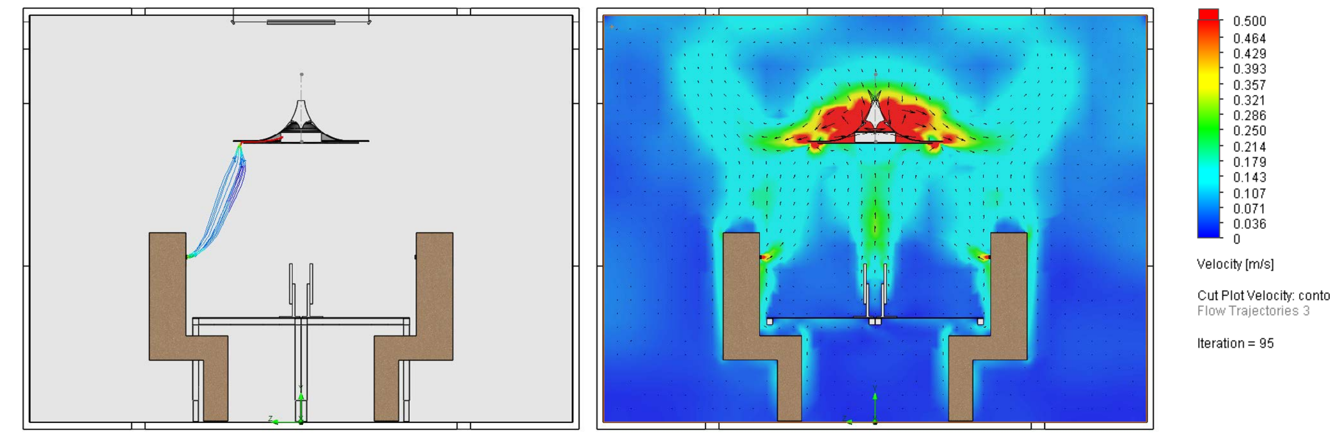


Figure 65
Hanging Lamp: Air velocity and path of user breath (left), air velocity cut plot (right)

The draft temperature plot in figure 66 shows a draft temperature of 0.5°C in the livable space of the user. The draft temperature around the user, the monitors are between 2°C and 3°C above room temperature. The room temperature is visibly homogenous.

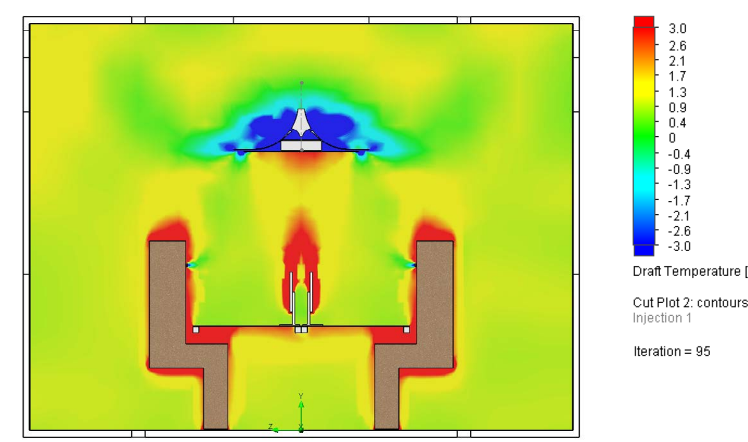


Figure 66
Hanging Lamp: Draft temperature relative to environment temperature (20°C)

Discussion

Comparing the results, the suspended lamp does capture the user's breath directly, whereas with the dividing wall this happens with multiple passes. Furthermore, the air exhaust and intake are separated with the suspended lamp but interfere with the dividing wall. Last, there is no decrease in draft temperature in the livable area of the user in the case of the suspended lamp, whereas there is a significant change of -3ºC for the dividing wall.

Furthermore, to capture all of the user's breath, a diameter of 1000mm – 1200mm and a volumetric flow rate of 200 m3/h is most effective.

According to Gijsbert van Marrewijk, these simulations are a good indication of the working principles of what would happen in a real-life situation. However, CFD simulations are always an oversimplification of a system. To be more accurate other ventilation systems and/or draft from open windows should also be modelled (personal communication, 2023).

Conclusion

From the CFD analysis it can be concluded that the suspended lamp outperforms in terms of product performance (priority 1) and user experience (priority 2). The air purifier effectively filters the air from the user's breath, separates the airflows from the intake and the exhaust, mixes room air preventing stratification, and creates a homogenous room temperature.

Furthermore, it was found that the volumetric flow rate must be 200m^3/h for two people. This is twice the predicted amount (50 m^3/h per person) as expected, which may be due to the proximity effect. Other additional requirements, i.e. the placement of the device, are shown in figure 67.

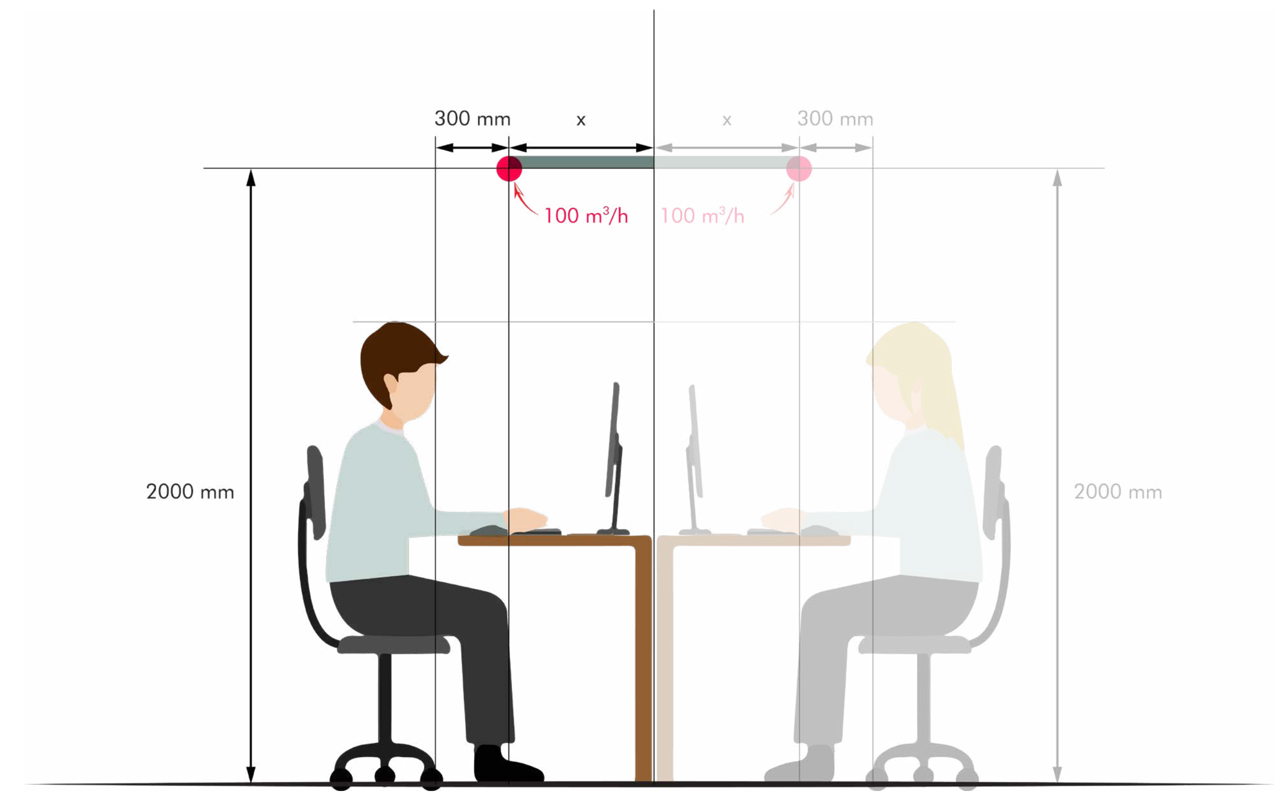


Figure 67
Additional requirements for positioning and volumetric flow rate of the Personal Air Filter as a result of the analysis in chapter 4.3

Additional Requirements:

- **MUST produce a volumetric flow rate of ~~50~~ 100 m3/h per person.**
- **MUST have the intake positioned within 2000mm measured from the ground and within 300mm horizontally from the user** (anything closer improves performance at a cost of user experience: e.g. noise).

4.4 - Advanced Concepting

This paragraph focuses on the development of a pendant lamp with an integrated air purifier that integrates the user experience (priority 2) alongside product performance (priority 1). The goal is to create a user-friendly design that seamlessly integrates an air purifier without causing discomfort or disruption. To achieve this, the necessary components and their respective sizes were sourced and realized through rapid prototyping. Midjourney[13] was used as a brainstorm tool to rapidly develop hundreds of ideas that fit the rough volume demands. These concepts were refined and selected based on the versatility and desired style relative to the target group (priority 3), with input from interior architect FLEX/design and Euromate. A design iteration step was taken to refine the chosen styling and embodiment direction, focusing on the look and feel of the device as well as a variety of methods for the user interface.

[13]
Midjourney is a generative artificial intelligence program that generates images from language descriptions called "prompts."

4.4.1 - Component Layout and Volume

Existing products were used to understand the possibilities and limitations with the size of the Personal Air Filter. Two air purifiers stood out for their compact shape and low noise production (max 50dB at full ventilation speed): Philips AC0819/10 and the Ikea STARKVIND (figure 68). For these devices, rough models were made of their volume and attached to the capture surface area and suspended in an office environment as seen in figure 69 and 70.

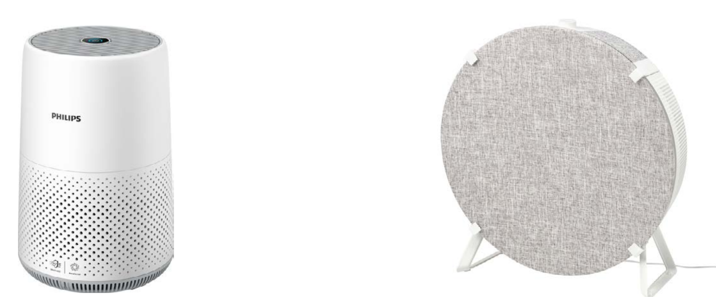


Figure 68
Philips AC0819/10 Air Purifier (left), Ikea STARKVIND Air Purifier (right)

Figure 69
Philips AC0819/10 Air Purifier dimensions added to 1000mm diameter disc in environment

Figure 70
Ikea STARKVIND Air Purifier dimensions added to 1000mm x 1000mm square surface in environment

4.4.2 - AI Inspired Design

Midjourney was used to efficiently produce a large number of unique images to inspire the client and myself. I designed in parallel with the tool to add to the proposed design. The most promising images were selected and plotted according to their defining shape to identify potential target areas. These were reviewed with Euromate and FLEX/Design to create four potential directions. Expert opinion from two qualified interior architect helped select the overall shape and style of the Personal Air Filter.

AI as a Brainstorming Tool for Style

The Midjourney generated designs and human generated designs are plotted on two shaping characteristics: overall form and surfacing (figure 71). The horizontal axis ranges from round to square, and the vertical axis ranges from simple to complex surfaces. The designs are also clustered in fitting office types; corporate office, high-end (meeting room), and traditional/formal office.

Figure 71
AI generated lamps organized by surfacing/ base-shape and categorized by office style.
Star = AI designed,
Circle = Designer,
Square = Existing Product

Target Client

The Midjourney generated designs and human generated designs are plotted on two shaping characteristics: overall form and surfacing (figure 72). The horizontal axis ranges from round to square, and the vertical axis ranges from simple to complex surfaces. The designs are also clustered in fitting office types; corporate office, high-end (meeting room), and traditional/formal office.

Figure 72
Office styles mapped on surfacing/base-shape matrix

Concepts Rendered in Context

Some of the 'Corporate Office' were rendered in their intended environment to give an impression of the look and feel. A more basic rectangular design was also rendered to explore all possibilities. Though AI is powerful (and more beautiful) in generating these renders, it lacks consistency to compare and contrast design effectively. For this reason, the renders were done by hand.

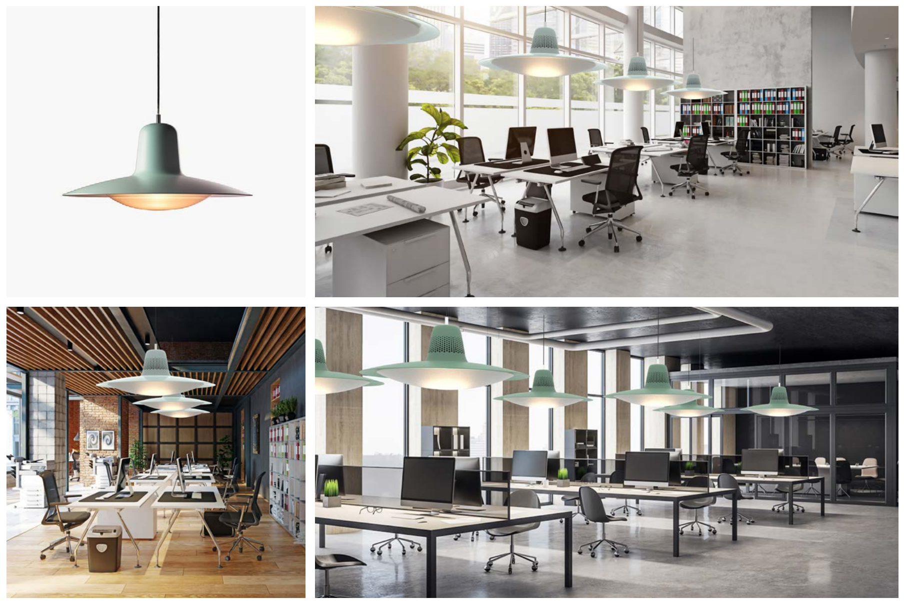


Figure 73
Nordic Pendant Lamp

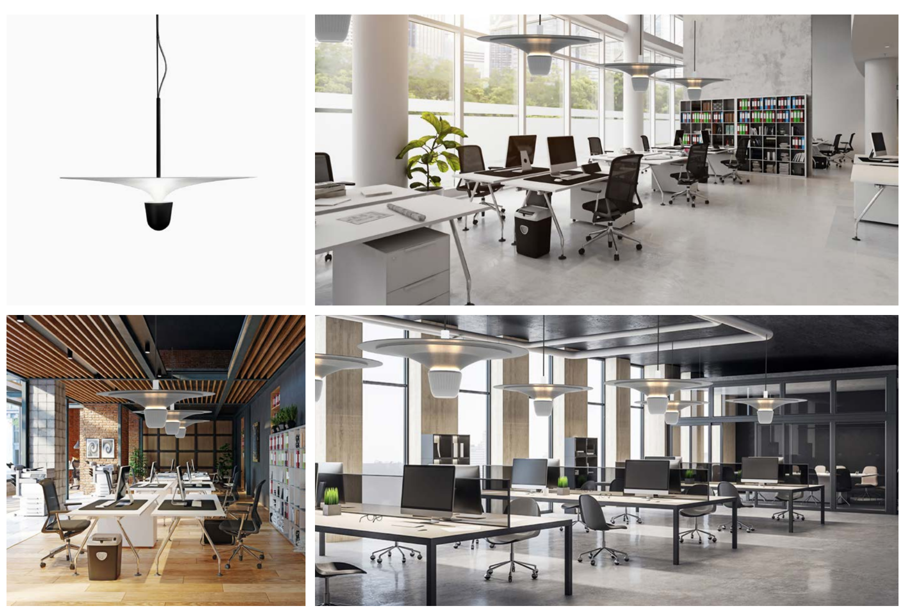


Figure 74
Elegant Pendant Lamp

Conclusion

These renders were discussed with FLEX/design and Euromate to make a design decision. The overall consensus was that the Nordic and Elegant Pendent lamps fit best within the intended environment. Furthermore, the prospect of other office contexts the round design fits in was also a key motivator to continue development of this design direction (personal communication, 2023).

Figure 75
Sound Panel Pendant Lamp

Figure 76
Basic Rectangular Pendant Lamp

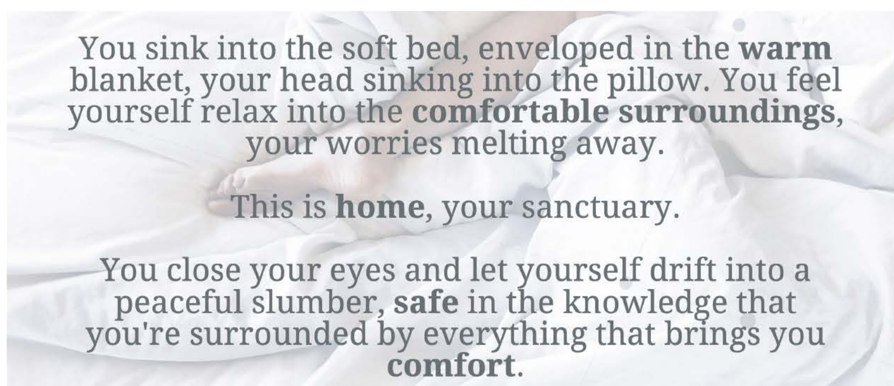
Concepting with Storytelling & Mood Boards

In the process of designing a product, storytelling and mood boards can be valuable tools to create a vision of its intended look and feel. In this project, three unique stories and accompanying mood boards were created with a focus on the emotions that can contribute to the user experience.

Accordingly, three concepts were designed based on the 'Nordic' and 'Elegant' designs. The first proposal before an iteration step with FLEX/design can be found in Appendix T

Lenticular

Soft Pod



Helios 03

Figure 77

Storytelling, moodboards and respective concept designs

4.4.3 - Concept Design Decision with VR

The three concepts in chapter 4.4.2 were pitched at Euromate to get feedback and make a design direction decision. Besides a slide deck, virtual reality (VR) was used to present the concepts to the client (figure 78 & 79).

Figure 78
Euromate employee experiencing the design proposal through VR

Conclusion

Both the Lenticular and Helios 03 concepts appealed to the client. Ultimately the Lenticular Personal Air Filter is better suited for developing a functional prototype as a final deliverable. It is simpler in construction, and there a higher chance to get the prototype functioning. The embodiment shape for the working mechanisms is proven by existing products, and therefore a smaller risk. Furthermore, it is expected that the Lenticular is easier to produce and therefore most likely cheaper.

Simpler, Less Risk, Cheaper.

Figure 79
Virtual Reality scene with concepts made in Blender

Figure 80
Soldering the connectors for the PCB

4.5 - Prototyping

A functional prototype of the Lenticular design was built for testing and verification. The three main goals of the prototype were to:

1. Visualise and prove the working mechanism with a smoke pen
2. Test ergonomics of controlling the device
3. Test noise level and effect on the user

The MEDION MD 19778 Air Purifier (figure 81) is used for components to build a functional prototype for the design validation. The 3D CAD model was made to fit the components of the air purifier.

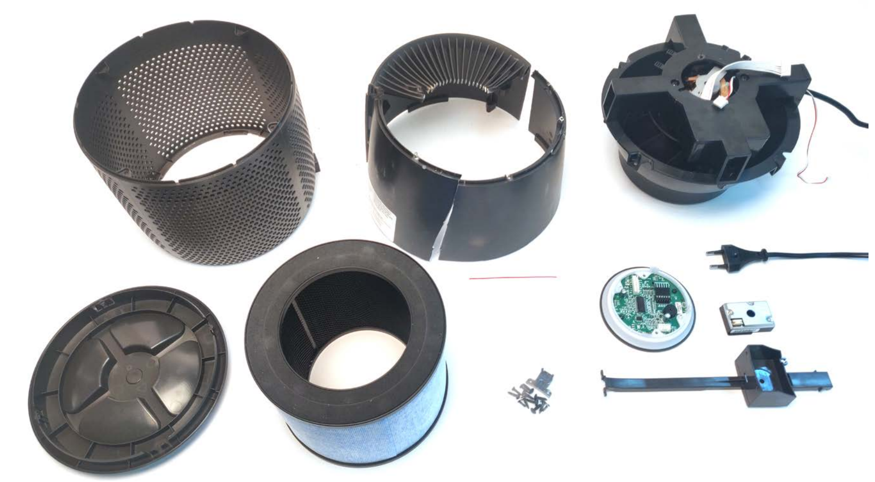


Figure 81
Dismantled MEDION Air Purifier to harvest working components

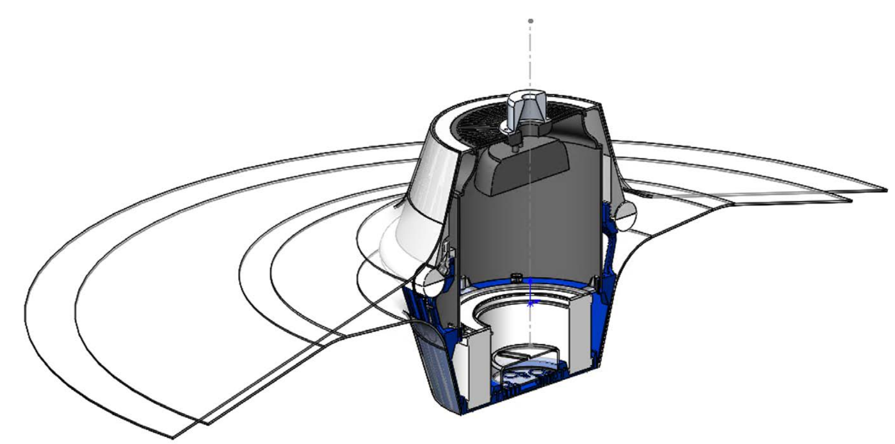


Figure 82
CAD model for prototype in SOLIDWORKS

A lengthy prototyping process, including 100+ hours of 3D printing, spray painting, making foam moulds by milling, sanding, coating in laminating epoxy, vacuum forming, trimming, soldering, and assembling, resulted in a final functioning prototype. This process can be seen in figures 83 – 87.

The prototype was built on a limited budget of 500 Euros, which resulted in the hoods being vacuum formed in quarter pieces to be able to produce them 'in-house'.

Figure 83
Spray painting 3D printed housing

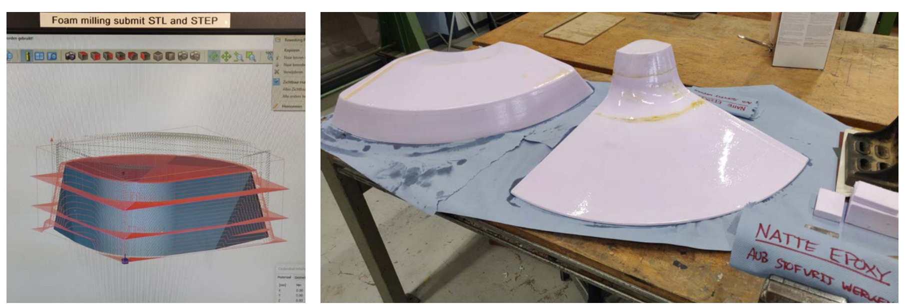


Figure 84
Milling foam moulds for hood, and preparing them with laminar epoxy coatings

Figure 85
Vacuum forming top and bottom hood in 1/4 pieces at the PMB, TU Delft

Figure 86
Assembling 1/4 pieces, trimming to the right size, and assembling components

Figure 87
First time the Personal Air Filter is suspended in the air

CHAPTER FIVE

DELIVER

During the Deliver phase, the final concept design proposal for Personal Air Filter will be presented. First, an overview of the product is given. Then, the key design drivers, namely the product performance, user experience, versatility and costs will be discussed.

5

5.1 - Introduction

This chapter delves deeper in the working principle of the Personal Air Filter and how it captures the user's breath to filter for aerosols, Design considerations like smart connectivity between multiple devices, the additional benefits it offers, and the design enablers necessary to facilitate this are discussed.

Subsequently, the interaction between the user and the Personal Air Filter for adjusting lighting and air filtering intensity is elaborated on. The ergonomics of operating the user interface on the device and the reasoning for providing an additional smartphone application are explained.

Furthermore, the versatility of office contexts where the Personal Air Filter can be implemented are showcased to give an overview of its conformability but also its limitations.

As described in the previous chapter (4.5), significant effort has been devoted to developing a functional prototype that serves as a Proof of Concept (PoC), which is used to validate the design drivers mentioned in chapter 3. The prototype is used for evaluating the product performance and comparing computational fluid dynamic (CFD) simulation results for the interaction with existing ventilation methods in the environment. Furthermore, tests are conducted with the intended users to evaluate the ergonomics and the need for a separate controller such as the smartphone application. Last, the production cost is estimated based on the CAD model of the prototype to get an indication of the final production price. The extent to which the design goals have been achieved will be determined through this evaluation, leading to recommendations for further research and development.

Figure 88

Summary visual of Personal Air Filter design proposal

A. Daylight lighting

B. Control with app

C. Touch UI on device

D. Filter aerosols from users breath

E. Smart connectivity

5.2 - Proposed Solution

The Personal Air Filter is a standalone air purifier that doubles as a pendant lamp, which is intended to be used in offices. It is suspended above desks to capture contaminated aerosols from the user's breath, thereby reducing the spread of airborne transmissive diseases. Furthermore, it improves indoor air quality by filtering pollen and other allergens. Overall, the cleaner air as well as local adaptive lighting improves the overall well-being of office employees.

Figure 89
Personal Air Filter suspended above office desks

The Personal Air Filter can be operated through the user interface on the device, or through an application on the user's smartphone. These give the user the option to adjust ventilation speed and lighting color/intensity. The device is also able to sense the user's presence to reduce the number of interactions by turning the purifier and the lighting on and off automatically. This 'smart mode' uses a particulate matter (PM) 2.5 and a passive infrared (PIR) sensor to adjust the fan speed and turn on/off the lamp.

Multiple devices can be suspended with the use of a track lighting system. These can be grouped by the user, which enables smart connectivity features such as optimizing the air filtering capacity by coordinating device operation. This reduces the noise the product produces as well as operational cost.

Figure 90
Multiple Personal Air Filters in context

Figure 91
Concept render of Personal Air Filter lighting

5.3 - Product Performance

In this chapter, the working principle of the Personal Air Filter to capture aerosols is explained. Furthermore, the necessary components and the design considerations are highlighted. Last, the conceptual functionality of interconnectivity between multiple devices and its benefits are explained.

5.3.1 - Working Principle

The Personal Air Filter is designed with the design principle 'form follows function.' The shape of the device is optimized to efficiently capture exhausted breath from the user. As a result, the intake of the device is extended to be within the propagation of the users' breath, which created a large capture area above the user.

The fan creates negative pressure (shown in blue), which draws air through the HEPA filter. By principle of the venturi principle[14], air travels at high speed (shown in red) in the narrow area between the two hoods. Correspondingly, there is high suction at the edge of the capture area. The filtered air is exhausted above the device at high velocity. Both the hood and the exhausted air flow separates turbulent airflow from itself and existing ventilation in the environment, thereby ensuring a stable airflow from the users' breath to the device.

[14]
When a fluid, such as a gas or a liquid, enters a narrow section (constriction) of a pipe, its flow area decreases. This leads to an increase in fluid velocity to maintain the same flow rate.

The cut-out of the Personal Air Filter in figure 92 gives a visual representation of how the air purifying process works and how the design effectively uses the components to achieve clean air. A radial symmetric design is chosen as it complements the embodiment design of the components. It is therefore, besides and aesthetic choice, also a logical choice to for the design to be round.

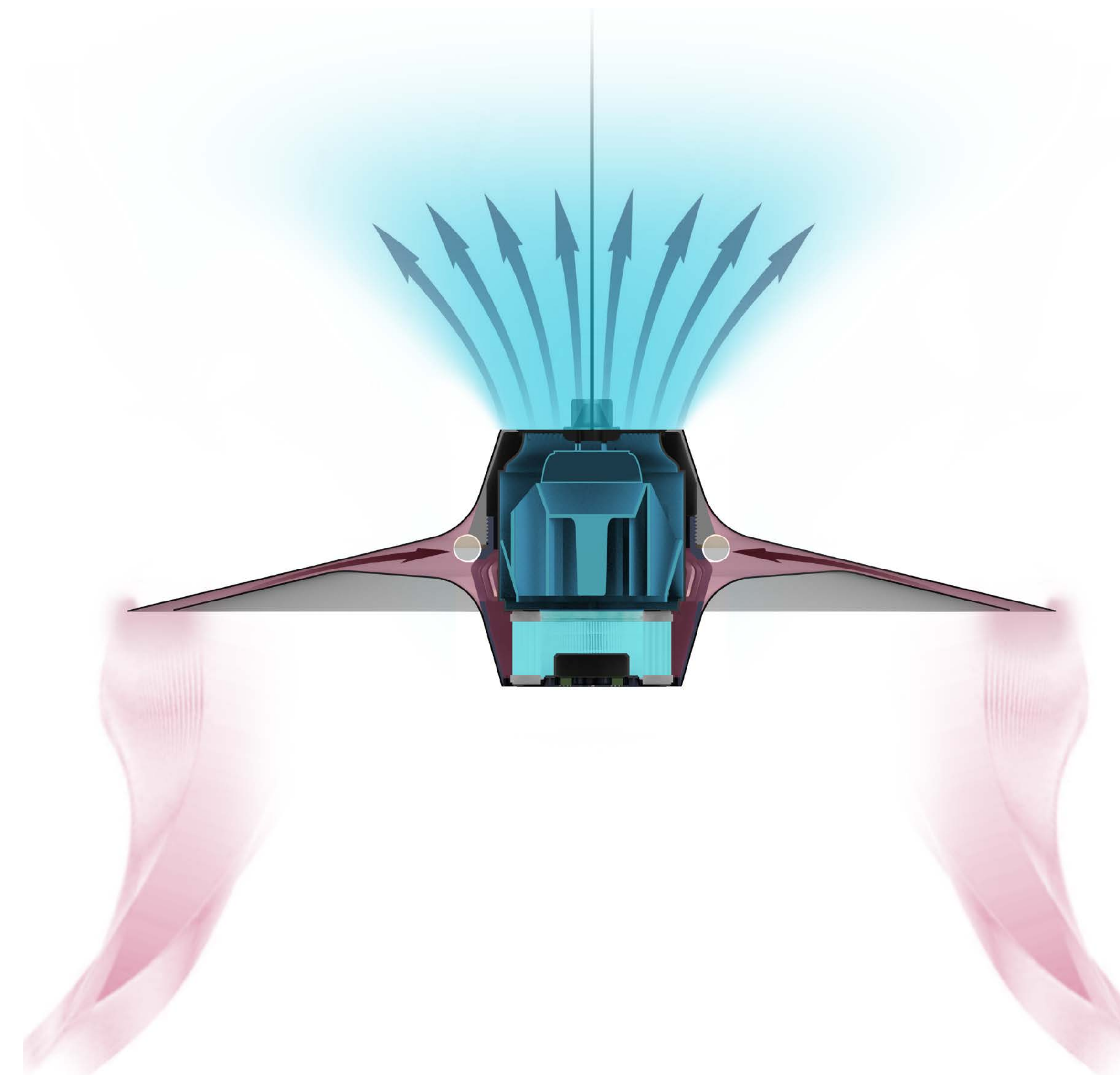


Figure 92
Working principle of the Personal Air Filter

5.3.2 - Components

The filter, sensors, and overall embodiment of the design are described below. It is interesting to mention that the embodiment design of the Personal Air Filter is not vastly different to other existing HEPA air purifiers.

A. Filtering Air

The main operating components are the forward inclined centrifugal fan and the HEPA filter. Note that there is not currently an active carbon filter, as these reduce the effectivity of the HEPA filter by creating more resistance (personal communication Euromate, 2023). These can however be easily retrofitted in the future.

B. Sensors

Like most other devices, a particulate matter (PM) 2.5 sensor is integrated, which is able to measure the concentration of aerosols and other pollutants in the air. A more unique element to the Personal Air Filter is the passive infrared (PIR) sensor on the bottom of the device. This enables the detection of people in the environment, enabling the 'smart-mode' described in the next chapter.

D. Lighting

For the lighting, a dimmable T9 20W LED lamp is used. A standardized component is preferable as it reduces development time and reduces overall cost price of the product.

E. Embodiment

The working components are packaged within the injection molded housing made of ABS and is composed of two separate parts. To bring the device together, the top and bottom opaque PETG hood 'sandwich' the device, creating the iconic aesthetic look of the Personal Air Filter.

All necessary components for the complete embodiment of the design can be seen in figure 93.

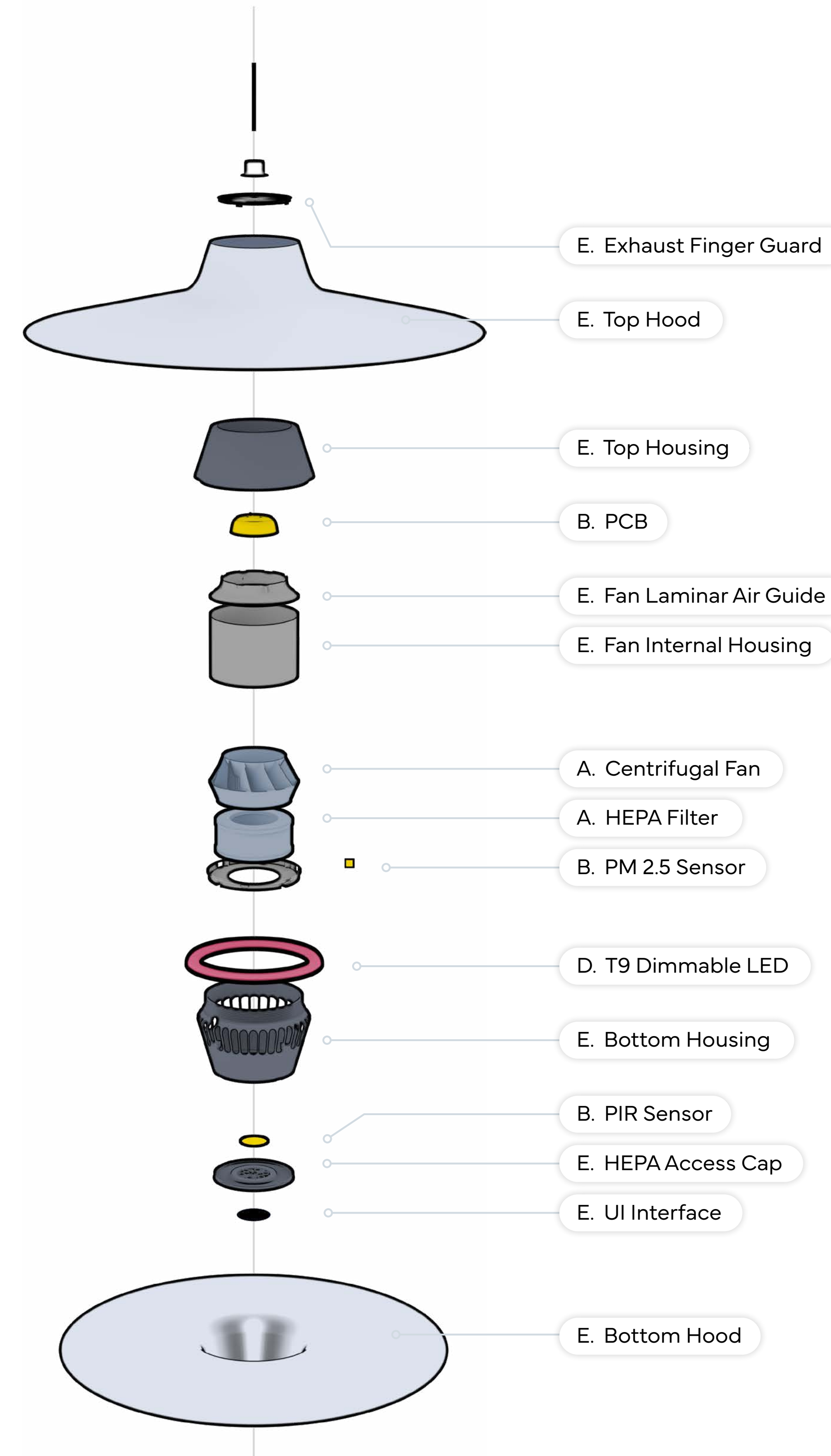


Figure 93
Abstracted exploded view of the Personal Air Filter

5.3.3 - Smart-Mode & Connectivity

Besides manual control, the Personal Air Filter offers automatic features such as smart-mode and connectivity.

Smart-mode

Smart-mode uses a PIR sensor to detect the presence of a user. As seen in figure 94, when a person arrives at the desk, the light will automatically turn on and the air purifier will start filtering air. When people leave the office, the air purifier can perform a 'deep clean'[15] as to fully remove all aerosols and pollutants.

[15]
Deep-clean is similar to the recommendation for leaving the cooking exhaust on for 15 - 30 minutes after cooking (Health Canada, 2020).

By measuring the concentration of particulate matter in the air, the Personal Air Filter can regulate the ventilation speed autonomously. PM 2.5 sensors are appropriate to use as the can detect aerosols (personal communication Euromate, 2023). As seen in figure 95, with more people in the environment the device will automatically adjust to filter the necessary amount of air to ensure a safe and clean working space. This feature can be selected by the user on the device with the icon seen in figure 96.

Figure 96
Smart-mode icon

Figure 95
Smart-mode fan speed for one person (left) or multiple people (right)

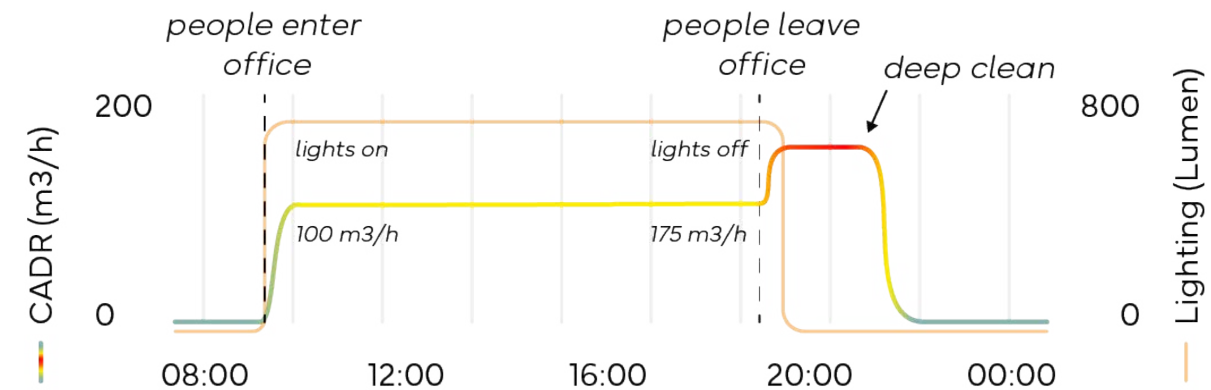


Figure 96
Smart-mode recognition of people entering or leaving the office, with consequent autonomous functions of turning the light and air purifier on/off

Connectivity (Conceptual)

To reduce noise of a single device, multiple devices work together to optimize the air filtering capacity. Multiple devices are actively filtering but with lower CADR than alone (figure 97). The fan can operate at a lower RPM and will therefore produce less noise. The user can enable this feature by setting up the connectivity in the app. This also enables the communication between devices.

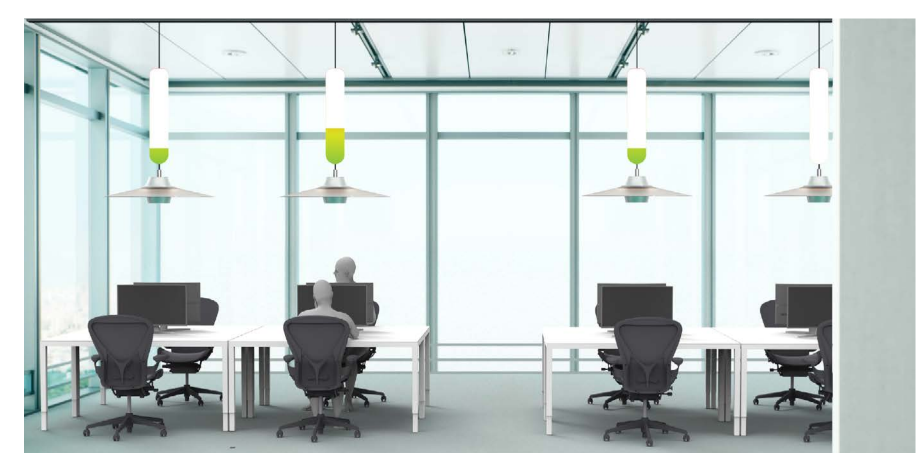


Figure 97
CADR distributed amongst multiple Personal Air Filter's to reduce the fan speed and thereby noise produced

5.4 - User Experience

The product experience is influenced by a range of factors of which only a few are touched upon. In this chapter, the user interaction with the device, such as using the user interface, the air quality indication, changing the HEPA filter, the lighting, and the smartphone application are discussed.

5.4.1 - User Interaction

A range of user interactions options for adjusting light and ventilation intensity, feedback on the air quality, and indicators that the HEPA filter were thought of during the development phase. These can be found in Appendix U. The UI options were discussed together with FLEX/design and became the foundation of the final proposed UI. Ultimately, the goal is to keep the UI as minimal and simple as possible without decreasing functionality (personal communication, 2023).

Initially the user interface was placed on the bottom of the device, as seen in the prototype in figure 98. After user testing (elaborated on in the validation), the feedback of the user interface was placed to the side of the device for improved ergonomics (figure 99). These design adjustments are already implemented in the final design proposal.

Figure 98
Old user interface on the bottom of the prototype

User Interface

The user interface enables the user to control the device settings, such as turning the device on or off, increasing or decreasing the ventilation rate/lighting intensity. Other options include smart-mode (as described in the chapter 5.3.3) and Bluetooth phone connectivity. The buttons work with sensitive touch capacitance to prevent the device from swinging. The user interface and icon meaning can be seen in figure 99.

Figure 99
User interface with icon labels

Air Quality Feedback

A subtle small light on the device indicates the air quality level measured in PM2.5 (µg/m3). The worse the air quality gets, the more threatening the color becomes. These levels are based on the US Air Quality Index (AirNow, n.d.).

The lamp is deliberately made small but clear enough to give the user the indication that a space should be safe to use. This may possible induce the feeling of security, knowing the chance of getting infected by an airborne transmissive disease may be less.

PM2.5 (µg/m³)	US AQI Level
0 - 50	Good
51 - 100	Moderate
101 - 150	Unhealthy for sensitive
151 - 200	Unhealthy
201 +	Very unhealthy

Figure 100
Air Quality Index (AQI) used for the Personal Air Filter

Figure 101
On/off button turns red to indicate HEPA filter needs to be changed.

Indication HEPA Filter Change

The device can recognize when this is necessary to replace the HEPA filter by measuring the resistance the filter gives. If this goes beyond a threshold (not defined in this thesis), then the HEPA filter is due for replacement. The on icon will turn red as seen in figure 101 to indicate to the user that the HEPA filter needs to be replaced.

Changing HEPA Filter

The user can change the HEPA filter by removing the 'HEPA Access Cap' as seen in figure 102. This cap is magnetically attached to the housing for easy removal. The device will not swing too much as the movement is in the opposite direction of how the Personal Air Filter is suspended. A replacement filter can then be installed.

There is a market opportunity for a Product-as-a-Service (PaaS) system for replacement HEPA filters. This is however not further explored within the scope of this report.

Figure 102
Changing HEPA filter visualisation

5.4.2 - Ergonomics

It is important that a wide range of people are able to use the Personal Air Filter with ease. Therefore, an analysis was conducted with DINED reach envelopes[16] to assess the ergonomic comfort of using the user interface.

[16]
DINED is an anthropometric database developed by the TU Delft. Reach envelopes determine how far a person can reach in a certain direction.

Reach Envelopes

It is common practice that a product is designed for P5 – P95 of the population. This standard was also used to see how people of P5, P50 and P95 stature will interact with the user interface of the device. Figures 103-105 show the posture of how each person uses the interface with data from the DINED reach envelopes (DINED, 2023). For every user, the desk height is adjusted to the stature height. From the reach envelopes, it is evident that p50 and p95 will reach the user interface with relative comfort. P5 however will struggle to reach the device without climbing on the desk.

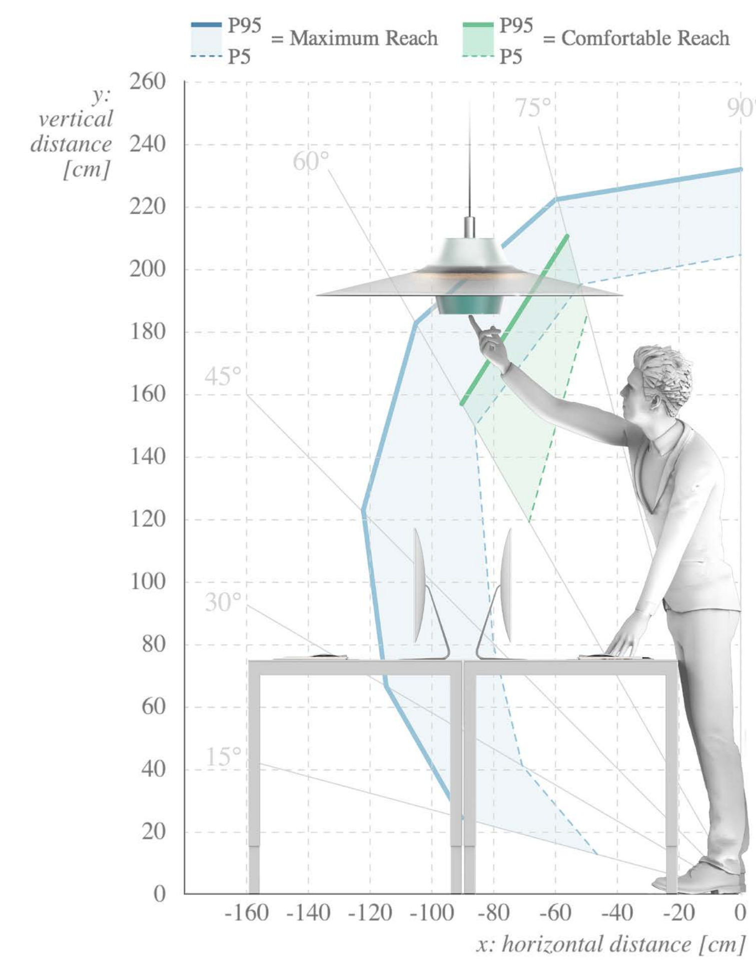


Figure 103
Reach envelope with Personal Air Filter of P50 stature user (20-30 years old) (DINED,2023)

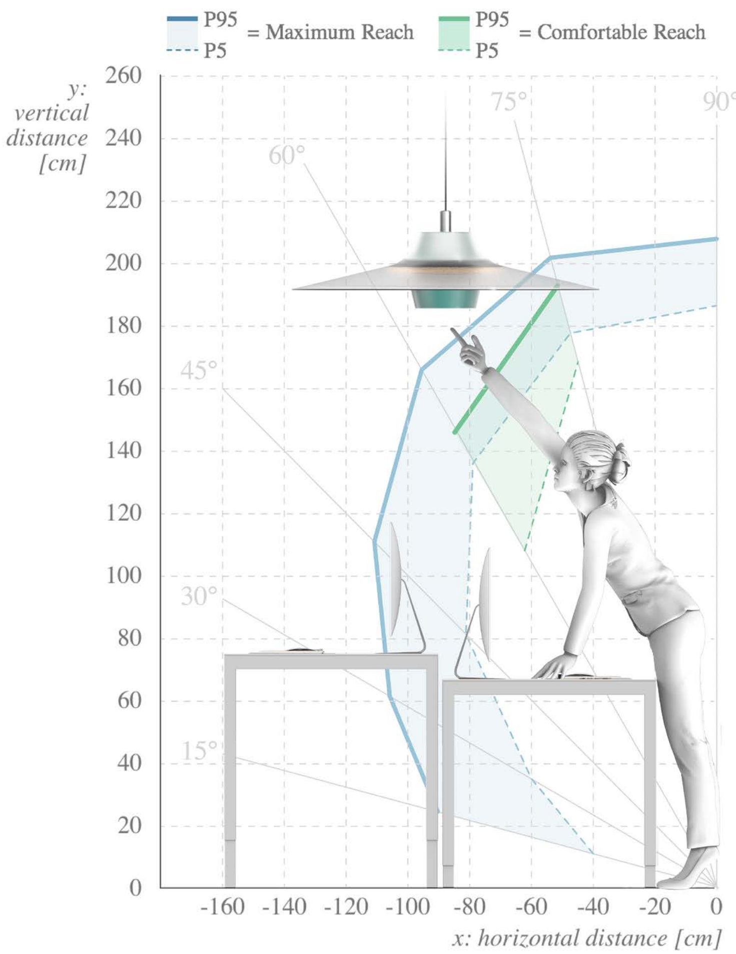


Figure 104

Reach envelope with Personal Air Filter of P5 stature user (50-74 years old) (DINED,2023)

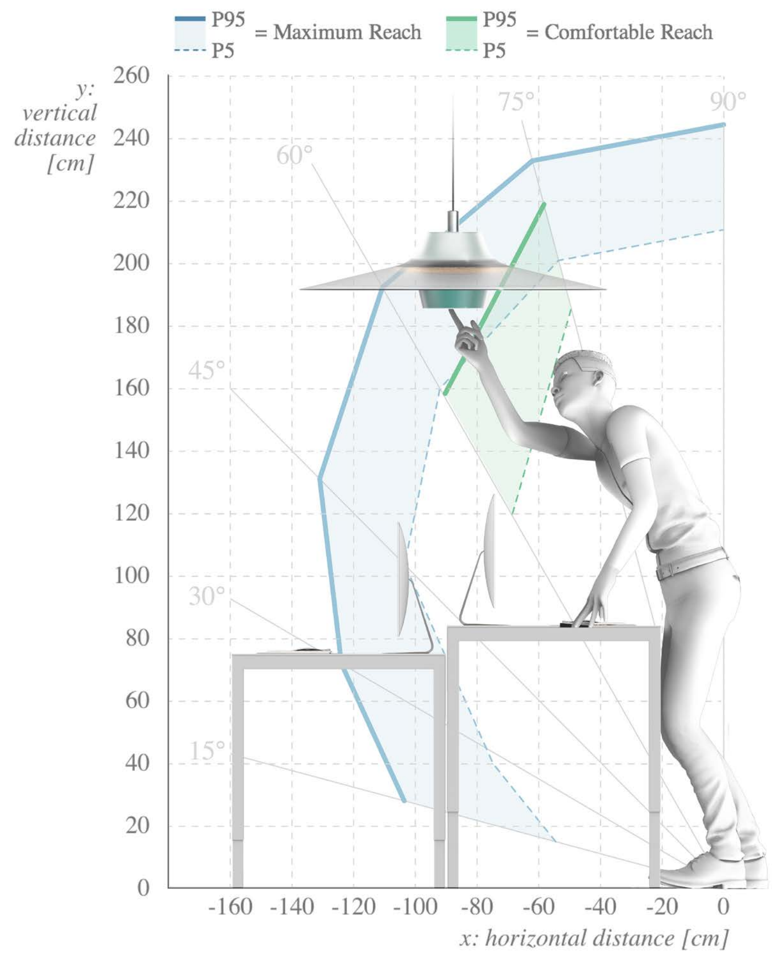


Figure 105

Reach envelope with Personal Air Filter of P95 stature user (20-30 years old) (DINED,2023)

Variable Height

From the reach envelopes analysis, it is clear that the height of the Air Purifier needs to be adjustable so all users can place the device at a comfortable height. People of smaller stature will want it lower and people of taller stature may want it higher to prevent hitting their head. This height adjustment can be done with a pully like system with the cable the device is suspended from as seen in figure 106. The friction of the cable guide will ensure the device will stay at the installed height.

Figure 106

Pulley system for simple height adjustment of the Personal Air Filter

5.4.3 - Lighting

An important factor contributing to the overall look and feel of the device is the lighting. The embodiment of the device was oriented around the dimensions of a T9 LED lamp fitting, and the hoods are made of semitranslucent PETG for creating and ambient lighting effect. Adjustability of both the lighting intensity and color provides the user with the necessary control to fine-tune the Personal Air Filter to their needs.

Lighting Intensity

The lighting intensity can be adjusted via the integrated user interface or smartphone application. A range of 150 to 1000 lumen is suggested to give a suitable array of choice. A dimmer light can enhance the atmosphere of the desk area to make working more comfortable and inviting. A bright light helps the user with concentration or better visibility of a task at their desk.

Lighting Color

For further improvement of user well-being, lighting color can be adjusted in the smartphone application. This too allows for better control of the atmosphere created by the personal air filter. Furthermore, Circadian[17] lighting (shown in figure 107) can be turned on by the user, which has been shown to enhance mood and alertness, increase productivity and performance, reduce fatigue and eye strain, and improve well-being (Figueiro et al. 2015).

[17]
Circadian lighting refers to a lighting system that is designed to mimic the natural patterns of light and darkness throughout the day to support our biological circadian rhythm.

Figure 107
Circadian light cycle with light color temperature (K) and time of day (Knoerzer, n.d.)

5.4.4 - Smartphone Application

Besides controlling the device with the integrated UI, the user should have the option to control the device without having to stand up regularly. To enable this, a mockup of a smartphone application was developed. The user can connect with the device either by scanning a QR code on the device or connecting via Bluetooth. Besides controlling the lighting intensity and ventilation rate, the app offers additional features such as viewing statistics, setting-up circadian lighting, and connecting devices in groups for interconnectivity. Figure 108 showcases the functionalities of the application.

The application was built in Adobe XD as a testing prototype. A working version of the application can be accessed through the QR code in figure 109. This application will also be used in the validation to test user needs for controlling the Personal Air Filter.

Alternatively, the following link can be used to access the application:

https://xd.adobe.com/view/b14a403c-e881-43d1-85b8-6b2192c981c0-e419/?hints=off

Figure 109
QR code for accessing prototype application for the Personal Air Filter (web/phone)

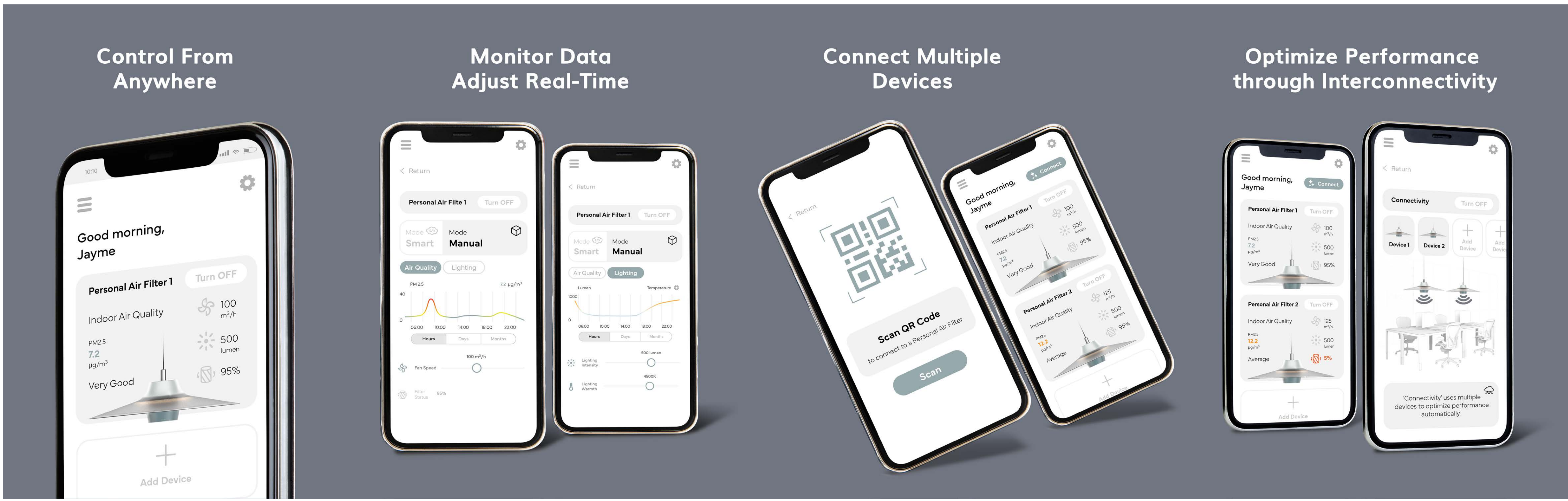


Figure 108
Smartphone app screens showcasing possible functionalities

5.5 - Versatility

The Personal Air Filter is applicable in a wide variety of office contexts besides desk areas, such as meeting rooms and and office lounge areas (figures 111 - 114). This versatility allows the design to be applicable in a wider market segment, ultimately increasing the chance for office managers and interior architects to purchase and implement the product. In this chapter, the track lighting system and height variability for standing desks that allow for greater versatility are elaborated on.

5.5.1 - Track Lighting System

As described in Chapter 2.3.1 (target scenario) there is a potential challenge with accessing power sockets from ceilings. Therefore, an optional track system where the Personal Air Filter can be suspended from can be purchased alongside the product. With the addition of the track lighting system, installing (multiple) devices is made much faster and easier. It also allows for horizontal re-adjustment of the positioning of the product in case tables are moved. Figure 110 shows how an existing track lighting can be used to suspend multiple devices. These can be recessed into the ceiling, surface mounted, or suspended.

Figure 110
Recessed (left), Surface Mounted (middle), Suspended (right) Track Lighting System for the Perosnal Air Filter

Figure 111
Render of the Personal Air Filter in a reception lounge

Figure 112
Render of the Personal Air Filter in an office with a high ceiling

Figure 113
Render of the Personal Air Filter in a meeting room

Figure 114
Render of the Personal Air Filter in an office

5.5.2 - Height Variability for Standing Desks

Chapter 2.3.1 (desk types) describes the current trend with height adjustable desks. It is therefore of importance that the Personal Air Filter is usable in a context with people using standing desks. With an intended suspended height of 1,9 meters, P95 of the Dutch population measuring at 1.9m will not get in the way with the device. However, if necessary, the height of the Personal Air Filter can be adjusted to fit both regular and standing desks. (figure 115).

Figure 115
Variable height mechanism used with standing desk setup

5.6 - Product Validation

In this chapter the Personal Air filter will be validated for both the product performance and the user experience by means of experiments, simulations, and user tests, and consultation with experts.

5.6.1 - Evaluation of Performance

To evaluate the performance of filtering aerosols, the functional was test with a smoke pen and the results of the CFD analysis were correlated. The results were discussed with an aerodynamics expert.

Evaluation of Effectiveness with Smoke Test

This scientific experiment aimed to assess the ventilation rates of an air purifier by utilizing a smoke pen to visualize air flows (figure 116). The smoke pen was positioned in the vicinity where the user's breath would typically be. The efficacy of different ventilation rates of the Personal Air Filter was examined as illustrated in figure 116. Although quantification is challenging, it was visibly evident that higher ventilation rates resulted in a greater capture of smoke. Specifically, at a ventilation rate of 200 m^3/h, nearly all visible smoke particles were filtered out. Surprisingly, even at lower ventilation rates, the effectiveness remained relatively high. However, it was observed that there was a more pronounced accumulation of smoke beneath the hood at ventilation rates of 50 m^3/h and 100 m^3/h.

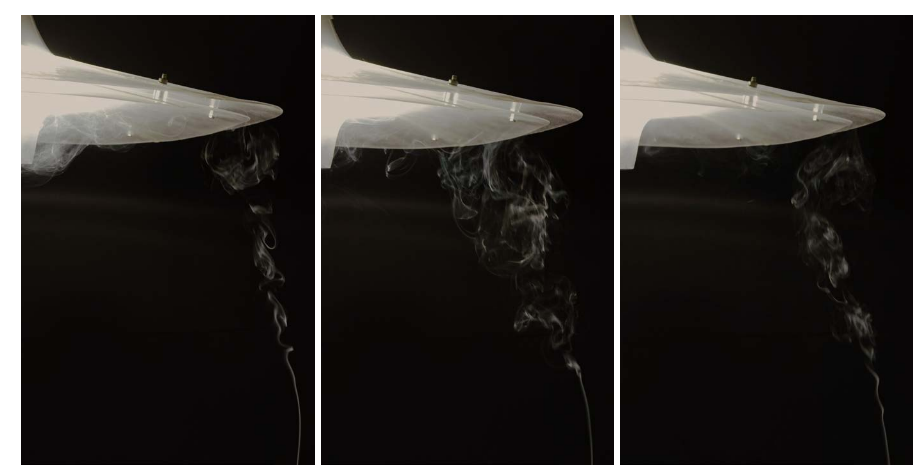


Figure 116
Smoke test with ventilation rate of 50 m^3/h (left), 100 m^3/h (midle), 200 m^3/h (right)

Additionally, an unintended discovery arose due to imperfections in the functional prototype. Some of the air was unintentionally filtered at the center of the device due to slight tolerances in the HEPA access cap, leading to a not fully airtight seal. This suction in the middle created a negative pressure, which attracted smoke towards the center, thereby effectively increasing the distance over which smoke could be captured.

Figure 117
Smoke buildup underneath hood of the Personal Air FIlter (50m³/h) (inverted colour)

Evaluation of Effectiveness with CFD Simulations

The effectiveness was tested by means of CFD simulation. As in chapter 4.1.1, the ventilation rate was tested at 50 m^3/h, 100m^3/h and 200m^3/h to compare and correlate (figures 118 - 120).

From the flow trajectory lines, it can be concluded that the CFD and smoke tests correlate closely. Similar patterns were observed, such as the quantity of air captured by the intake. Furthermore, the smoke buildup underneath the hood is also visible in the CFD simulations as there are flow trajectory lines similar to that of the smoke buildup in figure 116. Dissimilar to the smoke tests is the inefficiency seen for a ventilation rate of 50 m^3/h. In the CFD, little air was captured whereas the smoke test suggested to be more effective. Nonetheless, the CFD simulations show that 100 m^3/h and 200 m^3/h captures the breath at a range of ventilation flow rates.

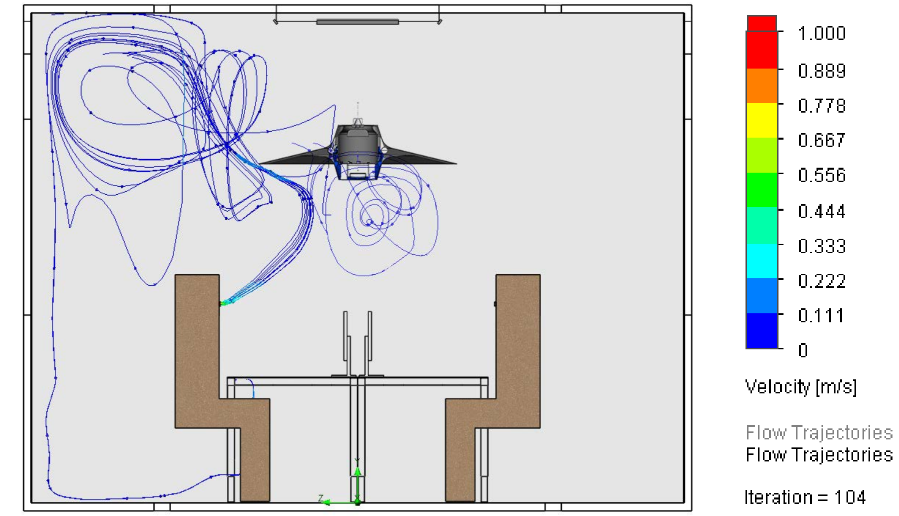


Figure 118
Flow trajectory lines of user breath at 0.0015 m³/h with a ventilation rate of 50m³/h

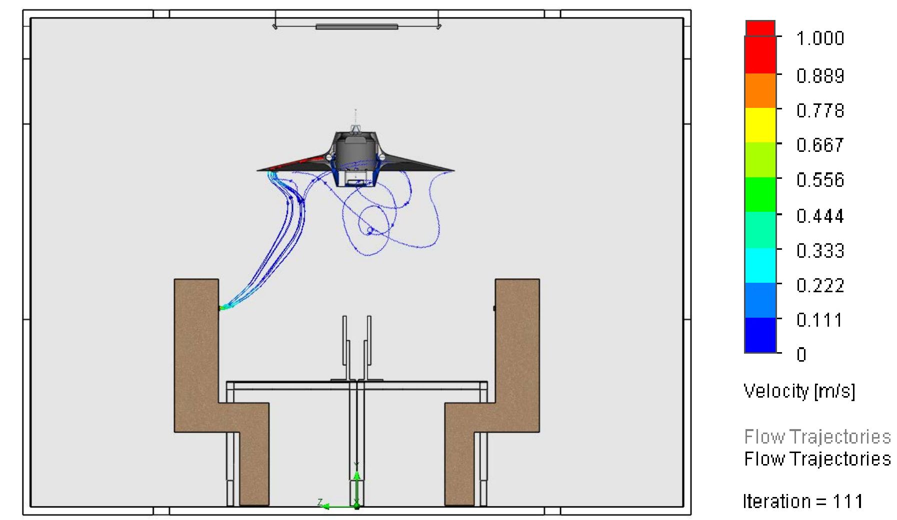


Figure 119
Flow trajectory lines of user breath at 0.0015 m³/h with a ventilation rate of 100m³/h

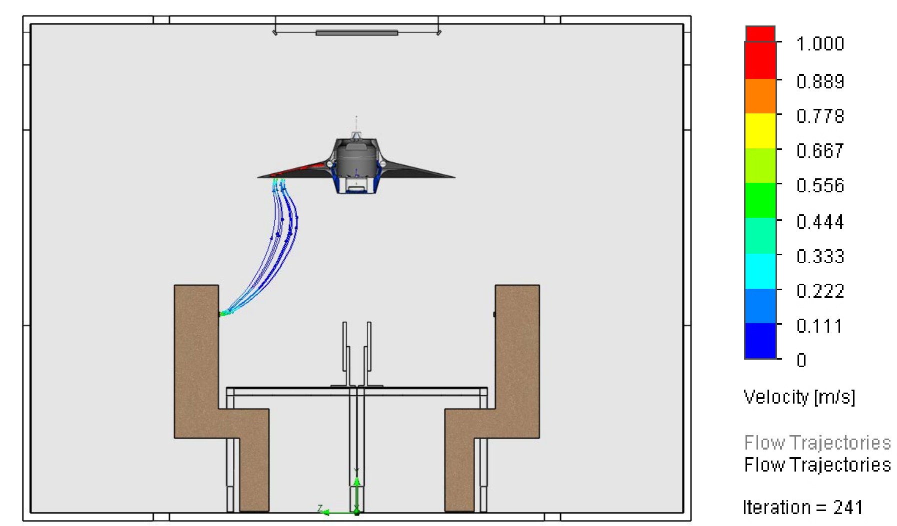


Figure 120
Flow trajectory lines of user breath at 0.0015 m³/h with a ventilation rate of 200m³/h

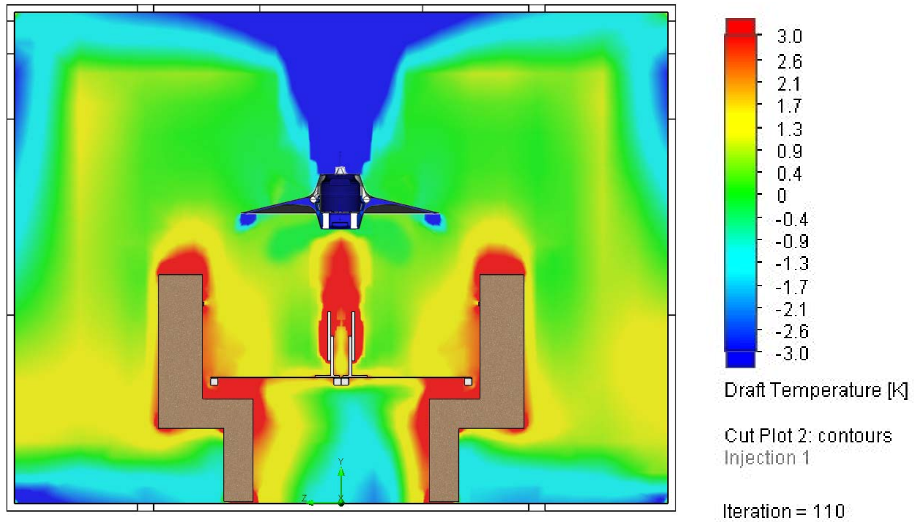


Figure 121
Draft Temperature (K) in environment at 293.15 K with a ventilation rate of 200m³/h

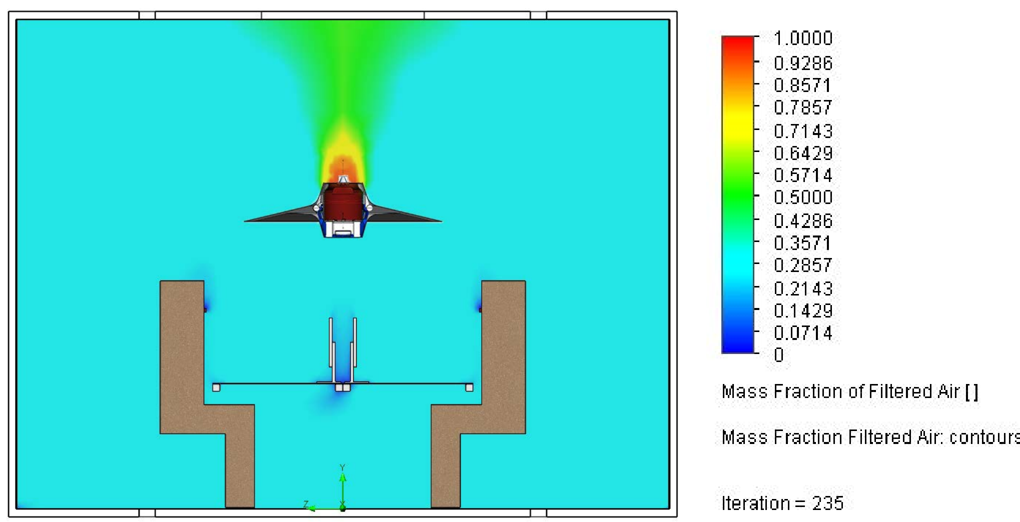


Figure 122
Mass Fraction of Filtered Air(%) in environment with a ventilation rate of 200m³/h after 5 minutes

Two important quantifications that the smoke tests don't reveal is the draft temperature and the mass fraction of filtered air in the environment. These give an indication for the user comfort and overall efficiency respectively.

The Draft Temperature simulation (figure 121) is similar to the results found in chapter 4.3.1 (CFD findings). The exhaust with high air velocity, induces a draft temperature of -3K. This is however expelled towards the ceiling away from the user.

Overall, at 200m³/h, the Personal Air Filter is expected to filter approximately 30% of all air within 5 minutes in a room of 120 m³ according to figure 122. This equates to roughly 4 Air Changes per Hour (ACH), which is above the desired 3 ACH defined in chapter 2.5.2[18] (volumetric flow rate requirements). This should suffice as the REHVA recommends 5 ACH is for filtering aerosols (REHVA, 2020b). Furthermore, the simulations indicate that there is no stratification in the room.

18
It is assumed that the environment the Personal Air Filter is placed in has existing ventilation of at least 2 ACH.

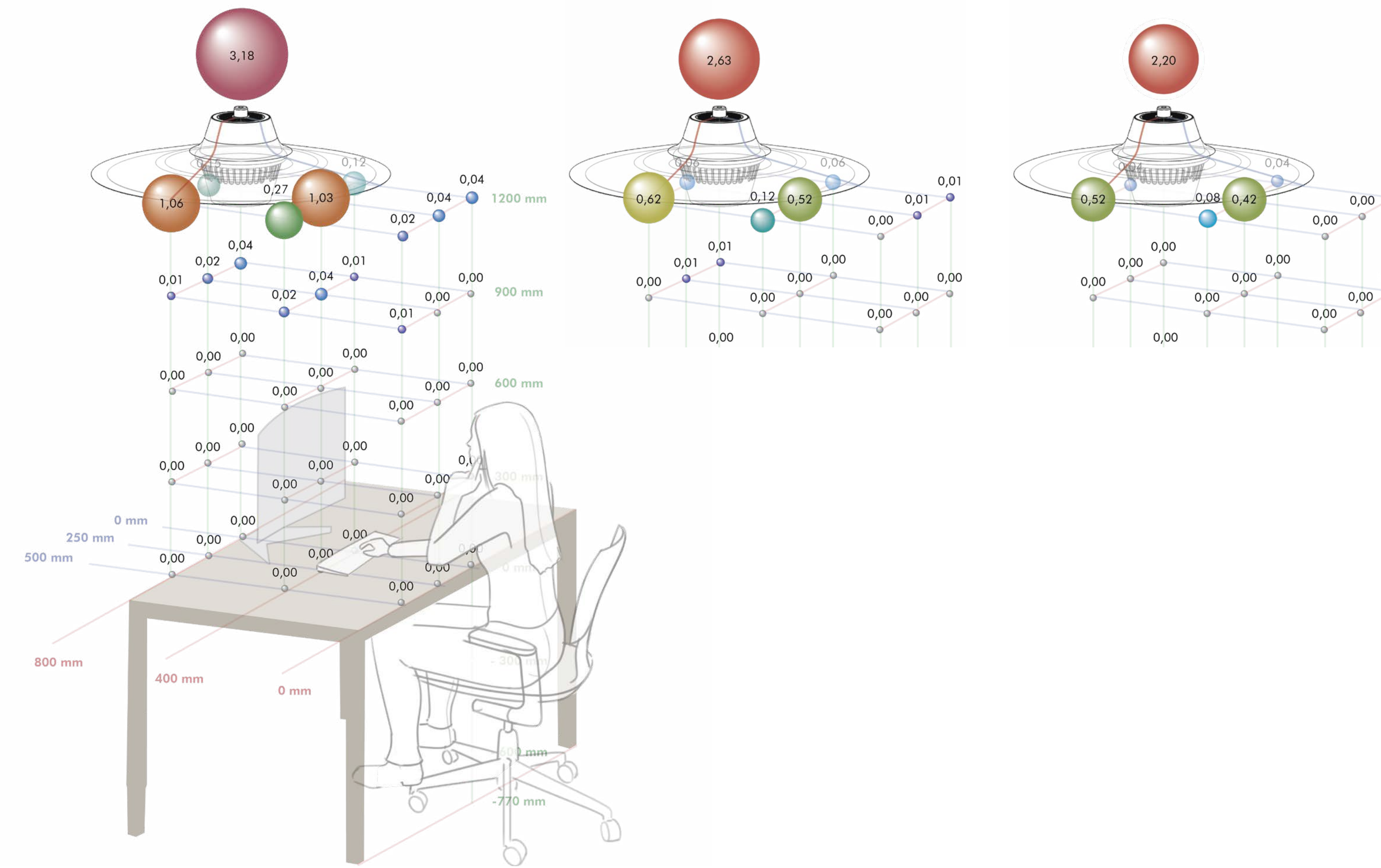


Figure 123
Air velocity measurements in livable zone of the user at 200 m³/h (left), 100 m³/h (midle), 50 m³/h (right)

Evaluation of Wind-Chill with Air Velocity Measurements

To confirm the results of the draft temperature, air velocity measurements were taken of the functional prototype with a Testo 405i anemometer. This uncovered where high air velocities are, which induce a wind-chill effect. Figure 123 shows the results for 200 m³/h, 100 m³/h and 50 m³/h. It is evident that the high velocities were measured at the intake at the edge of the hood. Underneath there were some movement of air, but below 0.20 m/s as defined in the requirements. Interestingly, the air velocity values for the intake also correlate with the CFD analysis in figures 118 – 120. Overall, in all instances there is no air flow measured within the working area of the user, which should ensure there is no discomfort.

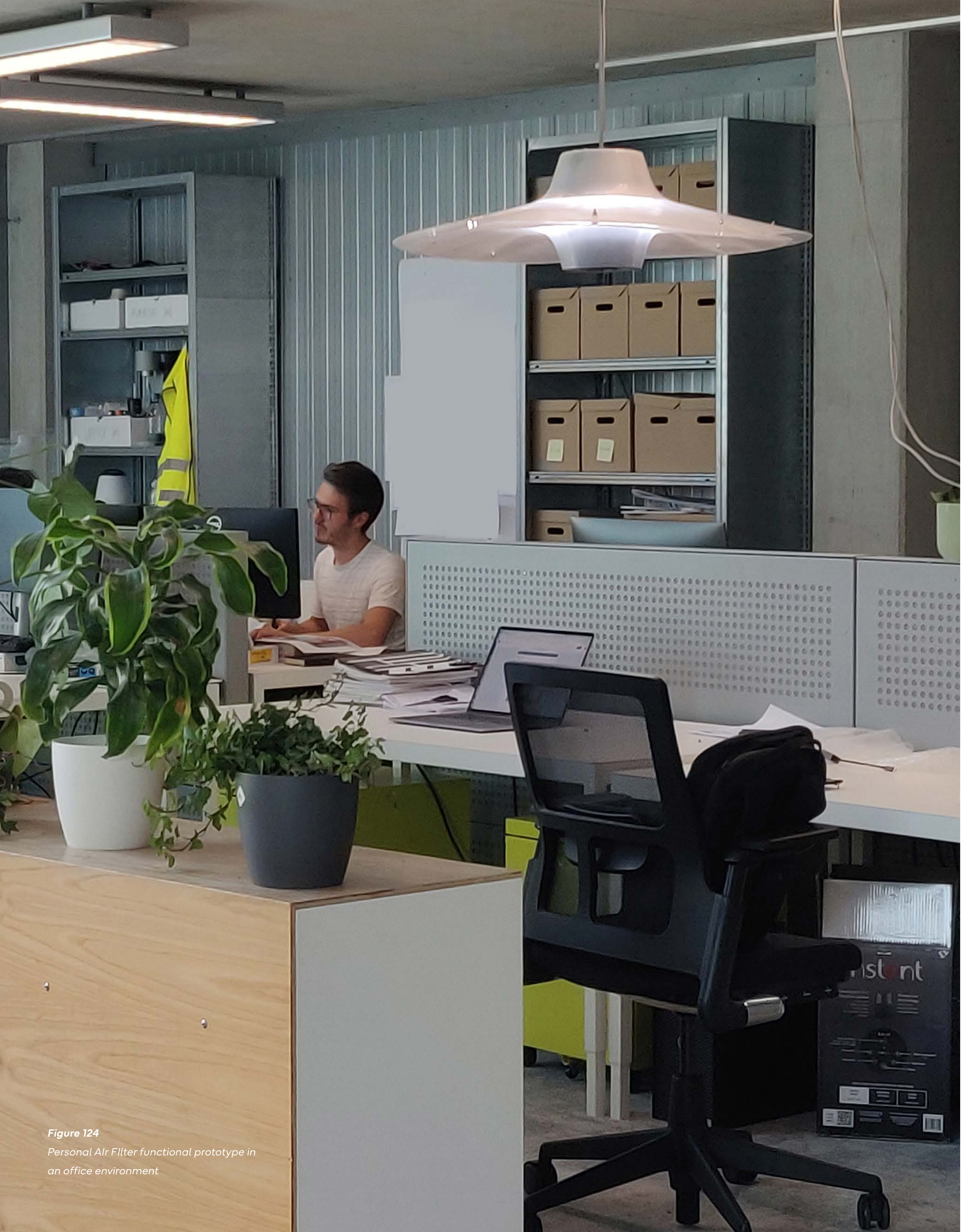


Figure 124
Personal Air Filter functional prototype in an office environment

5.6.2 - Evaluation of User Experience

To evaluate if in practice the interaction between the intended user and product is desirable, user tests for ergonomics and experience were performed. The ergonomics was tested with user tests and a questionnaire using the Likert Scale[19], and the experience was tested with observations and interviews. Pictures of participants are used with their consent.

Evaluation of User Interaction

For the evaluation of the user interaction, an existing interface from the Medion Air Purifier was used on the functional prototype. This interface was attached to the bottom of the Personal Air Filter. After performing actions with the device, participants were asked to rate statements on a Likert scale via a questionnaire. The test consisted of two parts:

1. Test the overall ergonomics of adjusting settings via the user interface on the device.
2. Evaluate the need for a separate controller in the form of a smartphone application.

Participants were selected to get a range of stature and age and sex. Figure 126 and 127 shows a summary of the participant demographics.

19
The Likert scale is a commonly used rating scale in survey research to measure respondents' attitudes, opinions, beliefs, or perceptions on a particular topic on a scale of 'strongly disagree' to 'strongly agree'

Figure 125
Medion UI on the functional prototype

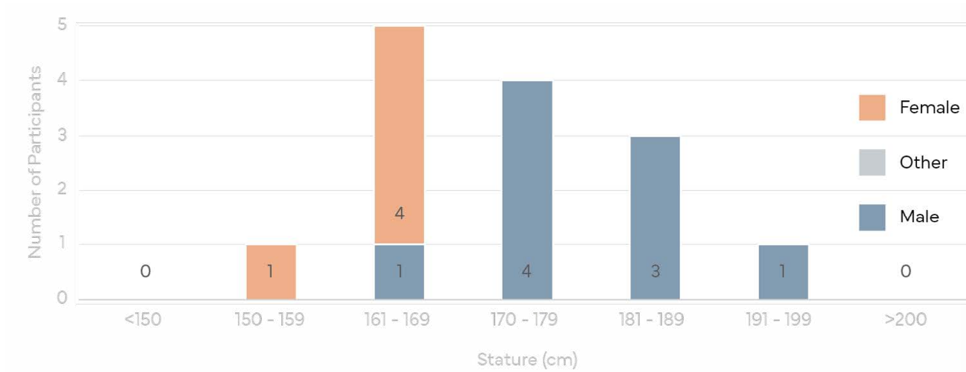


Figure 125
Height and sex demographics of participants for user experience test

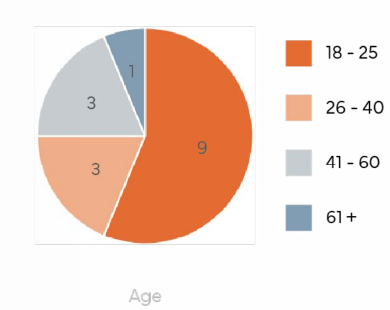


Figure 126
Age demographics of participants for user experience test

For Part A, participants were asked to turn-on the device and adjust settings from two positions. Position 1 was 60cm and position 2 was 80cm horizontally away from the device. After the participant had tried both situations, they were asked to what extent they agreed with the statement: "T*he interface of the pendant lamp was easy to reach*."

Figure 128
Participant of 155cm stature (left) and 191cm stature (right) adjusting settings from Position 2 (80cm)

Figure 129 show that at 600mm the participants agreed that they could generally reach the device easily with an average rating of 3.66 on the Likert scale. On the other hand, reaching the device from 800mm proved to be more challenging as it was rated a 2.66 on average.

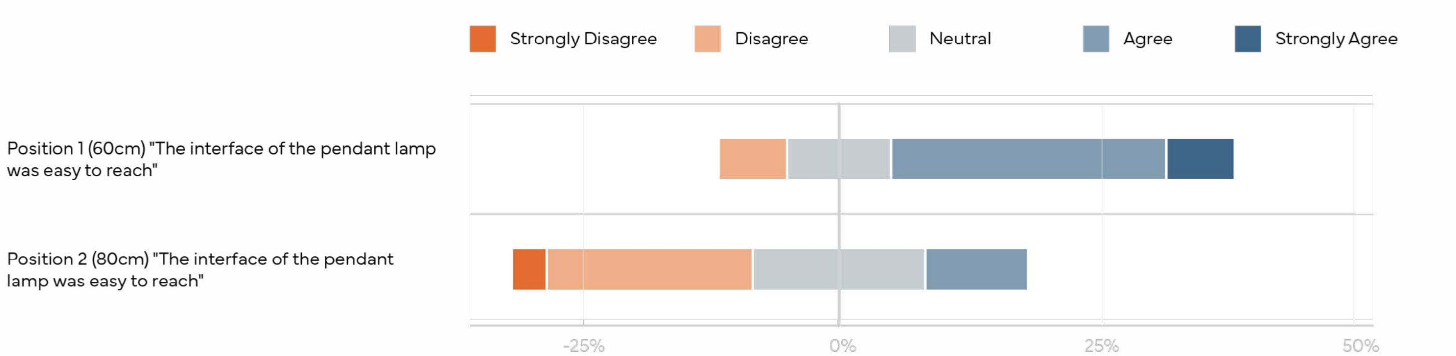


Figure 129
Likert scale ratings for "the interface of the pendant was easy to reach" for Position 1 (60cm) and Position 2 (80cm)

When looking at the ratings according to stature, it is interesting to note that the average rating for position 1 is slightly lower for people taller than 175cm, whereas for position 2 it is slightly higher. This can be explained by the awkward position tall people are forced into to see the display of the device as seen in figure 128.

Figure 130
Participant with 190cm stature bending to view the user interface

Table 1
Average scores for "The interface of the pendant lamp was easy to reach" for position 1 and position 2

	Scenario 1 (60cm)	Scenario 2 (80cm)
Average rating	3.67	2.67
Average rating (≤ 175 cm)	3.75	2.50
Average rating (> 175 cm)	3.57	2.86

Furthermore, the general consensus from the participants is that "the height of the lamp should be adjustable" as seen in figure 131. This confirms the notion of implementing some form of height adjustability such as suggested in chapter 5.4.2 (Ergonomics).

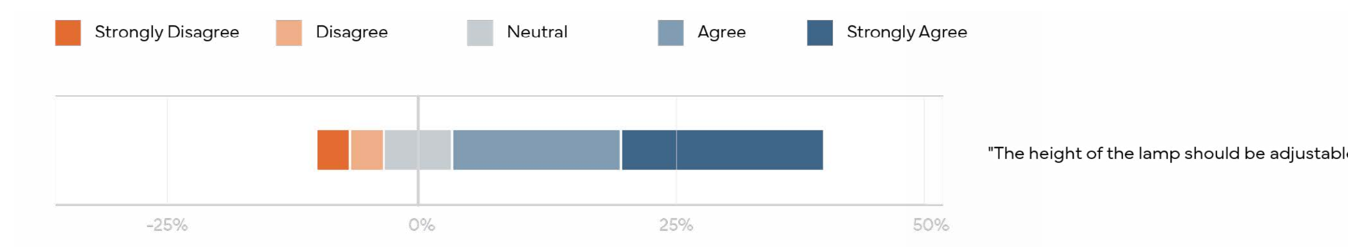


Figure 131
Likert scale ratings for "the height of the lamp should be adjustable"

To test the need for a separate controller in the form of a smartphone application, the participants were prompted with the task to connect to the device with their phone (without any further explanation). A QR code on the interface (figure 132) would link them to the prototype application presented in chapter 5.4.3 (smartphone Application). After using the application for some time, they were asked to answer the remaining Likert scale questions.

Figure 132
Participant scanning the QR code on the device

From the results in figure 132, several conclusions can be drawn. First, it is evident that in general the interface is intuitive to use and provides sufficient control. A functionality that was missing is adjusting the lighting as one participant noted *"Would be nice to change light intensity."* The QR too was an intuitive way to connect to the device, however some participants suggested that they preferred connecting via Bluetooth over a QR code.

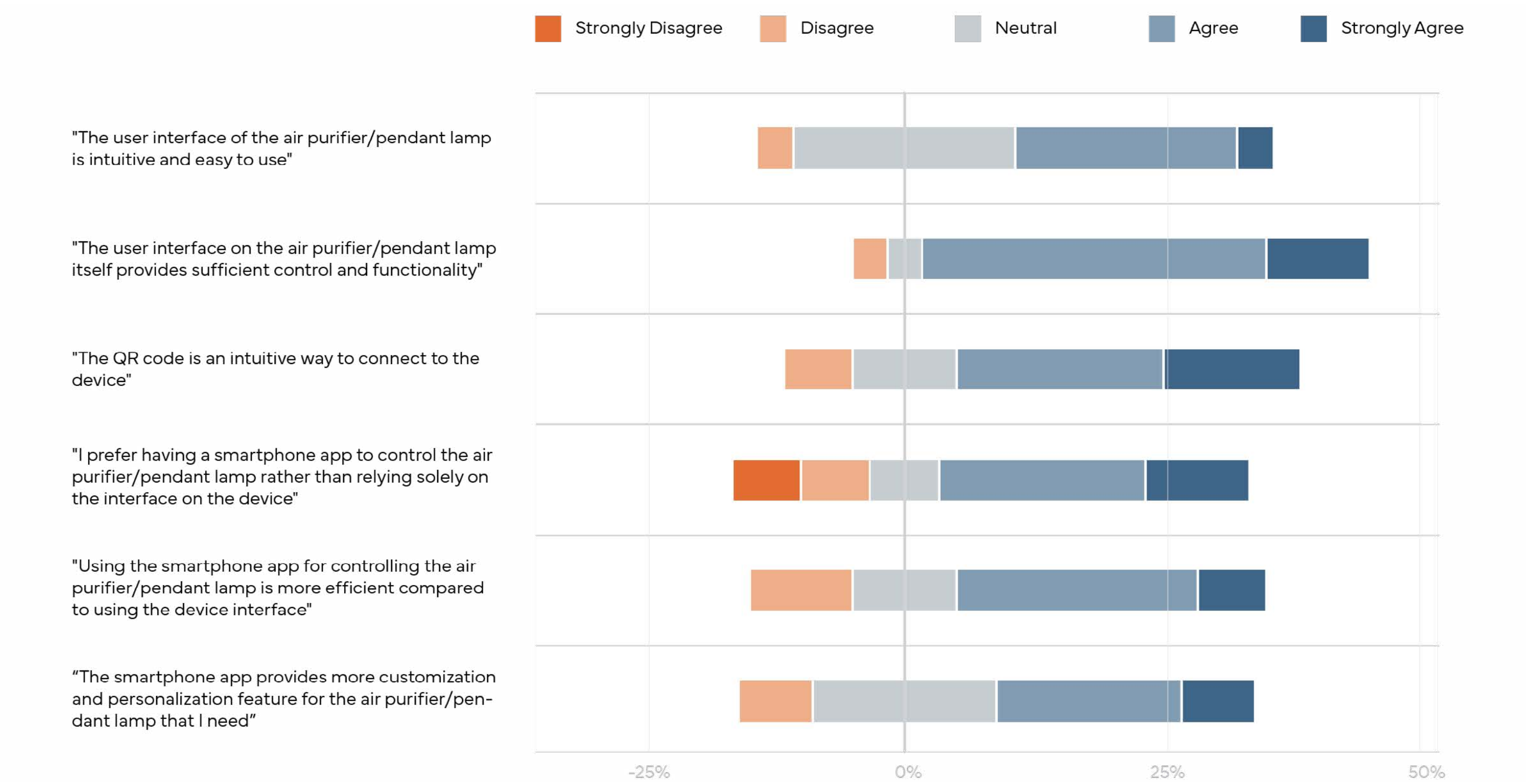


Figure 132

Likert scale ratings for evaluating user experience of the device UI and smartphone app

Opinion about preferring the use of an application was mixed but overall had a more positive reception. This was also a general trend for the statements 'the app ... is more efficient compared to using the device interface' and 'the app provides more customization and personalization features...'. Overall, the app poses no additional risk for dissatisfaction as it is an optional feature the user has to their disposal.

A noteworthy observation is the awkward position some participants had when scanning the QR code. A comparison between several participants can be seen in figure 133. While this task would not need to be done regularly in practice, it is still a potential discomfort for the user. This unergonomic user interaction is also applicable to seeing the user interface for people with a tall stature. A suggestion by a participant was to move the display of information and QR code to the side of the product.

Figure 133

Difference in scanning posture for tall stature (left) compared to smaller stature (right)

Evaluation of Noise User Experience

Besides a desirable interaction with the user interface, it is also of importance that the experience of using the Personal Air Filter for longer durations of time is comfortable. A test was devised to find out the user experience relative to the noise produced by the device. Three participants worked in an office for 2 hours on each ventilation mode. Table 2 shows the noise produced per mode/ventilation rate. The requirement: “MUST produce no more than an audible 45 dB at 100% CADR when measured from the user” is therefore not met.

Table 2

Noise (dB) generated by the Personal Air Filter at a ventilation rate of 50 m³/h, 100 m³/h, 200 m³/h

	Mode 1	Mode 2	Mode 3
Ventilation Rate	50 m³/h	100 m³/h	200 m³/h
Noise Level (dB)	43	49	60

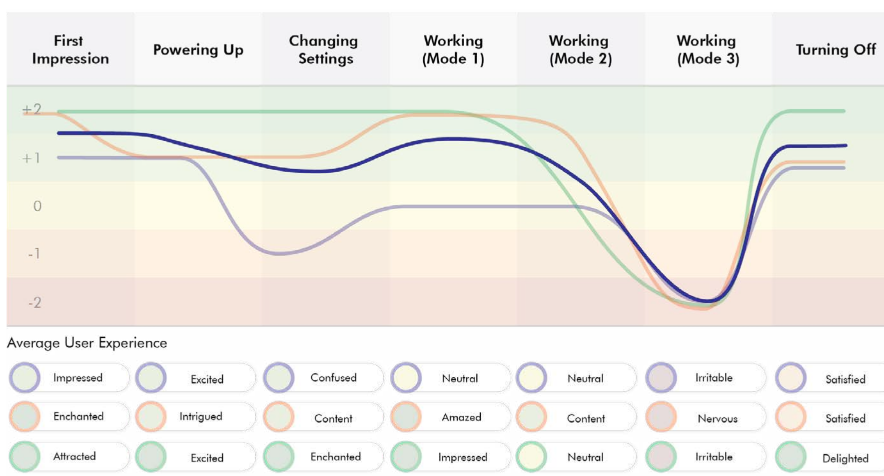


Figure 128

Participant of 155cm stature (left) and 191cm stature (right) adjusting settings from Position 2 (80cm)

A User Journey map was made as in chapter 2.3.3 (User Experience) to discover the ‘pain-points’ of the Personal Air Filter. Participants were asked after every activity to rate their experience with the help of the Junto Institute Wheel of Emotion & Feeling. Figure 134 shows a summary of the results and the complete list of individual results can be found in Appendix V. Though interaction with the user interface was also tested, it will not be elaborated in this chapter as the previous user test has already done so.

From the results it can be concluded that the noise generated by the Personal Air Filter is acceptable for Mode 1 and 2, and undesirable for Mode 3. All three participants noted a bad experience for the highest ventilation rate. On the other side, the quieter modes did not interfere or distract the user during concentrated work. One of them mentioned “I don’t even notice it!”

Conclusion

Overall, it can be concluded that the both the user interface and the product experience are desirable. The proposed interaction with the integrated UI on the device with an optional smartphone application was well received by the user, albeit some design adjustments. Some of the adjustments mentioned such as moving the display to the side of the product and enabling height adjustability to have already been implemented in the final concept. The user experience is not hampered at lower ventilation rates concerning the noise the product produces, however at the highest ventilation rate it is clearly unacceptable. It is therefore recommended to either use a better and quieter fan or limit the fan speed to not exceed a specified dB limit.

5.6.3 - Cost Estimation

To evaluate the viability of the design, a cost estimation for production of an initial series size of 1000 units is made. The current design is worked out to a concept level; therefore, the estimation is a rough indication of what the expected production costs are. An attempt is made by comparing to existing products and quotations from fabricators. Essential components for fabrication are the injection molded main housing and the vacuum formed hoods. Furthermore, off-the shelf components and assembly costs are also taken into account. For the cost estimation two scenarios were made, one low-end and the other high-end. Costs such as transportation, machine depreciation, and the development of the smartphone application has not been taken into account. A summary of the cost can be seen in table 3 and the full overview of the cost estimation can be found in Appendix W.

Table 3

Overview of production cost estimation in Euros based on calculations for a series size of 1000 units

	Low-end price estimation 1000 units (€)	**High-end price estimation 1000 units (€)**
Housing Injection Molding Aluminum Mold	155.000	206.000
Housing Injection Molding (material & fabrication)	19.000	19.000
Hood Aluminum Mold Thermoforming	12.000	16.850
Hood Thermoforming Price Top + Bottom (material & fabrication)	76.250 (2mm PETG Opal 39% LT)	102.600 (3mm PETG Opal 30% LT)
Off-the-shelf Fan Unit + HEPA filter	7.700	24.000
Off-the-shelf Lighting	3.800	3.800
Assembly	2.500	12.500
TOTAL 1000 units	**≈ 275.000**	**≈ 385.000**
TOTAL unit price	**≈ 275**	**≈ 385**

Housing

The housing of the Personal Air Filter consists of four essential parts that need to be separately fabricated by means of injection molding. Typically, ABS is used for these components as the material properties of such as impact resistance, heat resistance, dimensional stability, and surface hardness fit the intended use. For the high-end cost estimation, a higher surface finish and lower tolerance was assumed. For 1000 units, the expected cost is between €174.000,00 and €225.000,00.

Hood

The top and bottom hood will be fabricated through thermoforming, as this is suitable for shaping large polymer sheet material. Most likely standard thermoforming will be sufficient as the shapes have simple geometry. It is recommended to use 2mm or 3mm PETG, which comes in semitranslucent opal variations. The necessary thickness should be deduced during the engineering phase of the project. Overall, the cost for aluminum mold fabrication are between €12.000 and €16.850 dependent on where they are produced. For fabricating the 2mm top and bottom mold, the cost is estimated at €76.250, and for 3mm the cost is estimated at €102.600 (Personal communication Batelaan Kunststoffen, 2023).

Off the shelf components

The largest variability in price for the off the shelf components is the fan unit. Higher end components will be more silent but will cost significantly more too. For the cost estimation, three low-end models and three high-end models were compared. Furthermore, cables, PCB and other electronics are also included in this estimation. The overall estimated price for 1000 units for the low end is €7.700 and €24.000 for the high-end model.

The lighting too is an off-the-shelf component. For the prototype a T9 20W LED lamp from OSRAM was used. A range of T9 lamps were benchmarked to come to an estimated price of € 3.800 for 1000 units.

Assembly

The assembly costs are largely dependent on the labor costs. As there are very few components, the device can be bench assembled. Components that require assembly are the housing, fan, HEPA filter, electronics, and the lighting hoods. For the low-end model €2.500 was estimated whereas €12.500 was estimated for the high-end model.

Conclusion

Overall, the expected production cost will be between €275 and €385 dependent on the level of finishing and location of production. Furthermore, the production price can be drastically lowered by producing a larger series size than 1000 pieces as tooling costs amounts for roughly 60% of the current cost estimation. It can be argued that the requirement of a production price of €300 as described in chapter 3.4 (List of Requirements) is met in case the low-end fabrication is possible.

CHAPTER SIX

DISCUSSION

The discussion phase analyzes and interprets the results of the design process and validation. It provides an opportunity to reflect on the outcomes of the design, assess the benefits and limitations of the project, and discuss the implications of the findings on design recommendations.

6

6.1 - Design Benefits

When comparing the initial design proposal for the Personal Air Filter to the suggested solution, there are a few differences that stand out. These differences will be discussed in this chapter.

First of all, the Personal Air Filter is the first of its kind on the market. Unlike any other lamp-integrated purifiers available, it has been proven to effectively capture and filter the user's breath. Originally a concept, the product has now evolved into a working proof of concept. One significant design difference lies in the capture area of the device, which has been significantly increased in the new design. This larger surface area enhances the device's effectiveness in capturing aerosols. Additionally, the required volumetric flow rate and its impact on performance have been quantified, tested, and verified in this report. Furthermore, air stratification in the room is prevented as a result of the strategic placement of the exhaust. As a result, it is expected that the use of the Personal Air Filter will contribute to reducing the spread of airborne transmissive diseases.

Next to that, the design has been developed from a user-centric approach to create a more desirable product. By making the lighting a core feature of the Personal Air Filter, the device serves a greater purpose than solely filtering air. The local lighting creates a more comfortable and homelike atmosphere for the desk area in offices, going along with current trends in office interior design. Additionally, the new proposed design is less invasive and more attractive than the original solution.

Moreover, the design of the Personal Air Filter has been developed from a user-centric perspective, resulting in a more desirable product. By integrating lighting as a core feature of the device, it serves a greater purpose beyond air filtration alone. The localized lighting creates a comfortable and homelike atmosphere in office desk areas, aligning with current trends in office interior design. Furthermore, the new proposed design is less obtrusive and more aesthetically appealing than the original solution.

Furthermore, the new Personal Air Filter offers increased versatility in its implementation. By transitioning to a standalone device equipped with its own fan and HEPA filter, it can be utilized in various contexts. The integration of a track lighting system and adjustable height feature simplifies installation and allows users to customize the device according to their specific needs.

In summary, significant progress has been made towards the development of a final product for the Personal Air Filter; an innovative device that has the potential to improve the health and well-being of employees in the workplace.

6.2 - Design Limitations

Although the validation showed many positive outcomes, there are some drawbacks and areas that require more attention to improve the overall design of the Personal Air Filter.

Noise

An important requirement that was not met is the noise produced by the device. Based on literature and user testing, a limit was set at 45dB for the highest volumetric flow rate. At 200m^3/h, the 60 dB is much too high for a desirable product. On the bright side, validation of ventilation performance showed that 100 m^3/h was also very effective in capturing the smoke. Furthermore, a low-cost fan was used, therefore there is room for improvement with better design and better components.

Interaction with Existing Ventilation

The performance validation of the design has not yet included testing the interaction with commonly used ventilation methods in office environments, such as HVAC systems and positive pressure outlets. These existing ventilation systems may potentially disrupt the airflow of the user's breath, therefore it is important to address this issue.

While the interaction between the Personal Air Filter and these ventilation methods has not been thoroughly tested in the current performance validation, the design has taken into consideration the presence of these systems and implemented features to minimize their impact on the effectiveness of the device. Measures have been taken to mitigate any potential interference. For instance, the hood and exhaust components of the Personal Air Filter are designed to block and redirect any interfering airflows caused by the existing ventilation systems.

User Interaction Reaching Distance

The design of the Personal Air Filter prioritized optimizing the capture of aerosols from the user's breath, which resulted in a specific height range. However, this height specification did not originally take into account the ergonomic needs of users with heights outside the average range. As a result, taller users may find it inconvenient or even uncomfortable to control the device effectively, while shorter users may struggle to access the controls due to the height limitation. This issue is particularly pronounced for larger tables with a depth of 80cm, which are at the upper range, while it is less of a concern for smaller tables.

Changing HEPA filter

An important aspect that was not validated and will likely be a threat to user experience is changing the HEPA filter. Besides accessibility to reach the filter for people of all heights, the Personal Air Filter will swing and rotate with the current design.

Suitability of Design in Office Context

While interior architects have been involved in different stages of the design process, there is currently no comprehensive confirmation regarding how well the Personal Air Filter will fit into the intended environment. Although design renders provide an impression of certain scenarios, they do not fully depict the complete picture of how the device will look and feel in its intended setting.

6.3 – Design Recommendations

There are some areas that require improvements before engineering and producing the Personal Air Filter. This chapter aims to give direction on how to overcome these limitations, as well as provide design recommendations.

Optimize air flow of exhaust and hood edges

First and foremost, there is room for improving the effectiveness of the Personal Air Filter with a minor design alteration. Ir. Van Marrewijk, an aerodynamics expert, suggests adding a skirt upwards or downwards at the edge of the hood. This results in a longer path for the air to travel, thereby effectively increasing the operational range of the intake. Some level of testing can be done with the existing Proof of Concept to find the most suitable solution. By expanding the range, there is a possibility to downscale the size of the Personal Air Filter.

Size

Indeed, it is evident that the overall size of the Personal Air Filter is relatively large due to the necessity of effectively filtering aerosols. However, enhancing the desirability of the device could involve reducing its size, making it easier to implement and more aesthetically pleasing in office environments. Achieving this objective may require optimizing the airflow, as mentioned earlier, and finding a suitable balance between performance and size, thereby creating opportunities for improvement.

Furthermore, the current design of the Personal Air Filter is focused on filtering 100% of the user's breath, ensuring comprehensive filtration. However, exploring the possibility of filtering air to a slightly lesser extent while still maintaining satisfactory performance may present viable options. By finding the right trade-off between filtering efficiency and size, it could be possible to reduce the device's overall dimensions without significantly compromising its effectiveness.

Burden of Proof

While the foundation has been set for validating the effectiveness of the Personal Air Filter in filtering the user's breath, it is important to acknowledge that this alone does not provide conclusive evidence of its overall effectiveness in reducing the transmission of diseases in office settings. To make such a claim, it would be necessary to conduct extensive real-world tests by a reputable third-party organization like TNO (Netherlands Organization for Applied Scientific Research) to provide clear and convincing evidence.

Quantification of the extent to which the Personal Air Filter reduces the spread of airborne transmissive diseases can be a significant unique selling point for Euromate. Demonstrating concrete data and evidence regarding the device's effectiveness in reducing disease transmission would offer a compelling advantage over competitors and instill confidence in potential customers.

Development of Interconnectivity through the Smartphone Application

In the design proposal, the suggestion of using interconnectivity between multiple devices through a smartphone application is a promising concept. The application can serve as a design enabler for connecting the Personal Air Filter devices and facilitating communication between them. To effectively implement this feature, it is essential to revisit and develop the design proposal for the application in collaboration with user experience (UX) designers. The involvement of UX designers is crucial in ensuring that the smartphone application provides a seamless and intuitive user experience.

Further Development and Integration with Track Lighting System & Height Variability

When considering the use of a track lighting system to suspend multiple Personal Air Filters from the ceiling, it is crucial to select a suitable system that can accommodate the weight of the devices. Given that the current proof of concept weighs 9kg, it is necessary to choose a track lighting system that has the required load-bearing capacity.

Sustainability Considerations

There are several possibilities for implementing sustainable practices that can enhance the environmental impact of the device.

One potential approach is to integrate a Product-as-a-Service (PaaS) system for the HEPA filters. This model would involve providing the filters as a service rather than selling them as individual products. Euromate can take responsibility for the proper disposal and recycling of used filters, ensuring their safe and environmentally friendly handling. This not only reduces the burden on customers in terms of filter disposal but also allows for efficient management of filter waste and promotes a circular economy.

In addition, considering alternative filtration technologies could contribute to the sustainability of the Personal Air Filter. While HEPA filters are highly effective, they are not recyclable due to the accumulation of particulate matter. Exploring alternative filter options, such as electrostatic filters, could present a more sustainable solution. Before implementing any changes, conducting a thorough Life Cycle Analysis (LCA) is crucial. This analysis would assess the environmental impact of the Personal Air Filter throughout its entire life cycle, from raw material extraction to disposal, and identify the best alternative filtration means from a sustainability standpoint.

Furthermore, sustainable material choices and energy-efficient components should be prioritized in the design of the Personal Air Filter. Utilizing eco-friendly and recyclable materials, as well as optimizing energy consumption during operation, can significantly reduce the environmental footprint of the device.

By incorporating sustainable practices into the design of the Personal Air Filter, Euromate can align with the growing demand for environmentally friendly solutions and enhance customer satisfaction. It is important to approach sustainability holistically, considering the entire life cycle of the product and analyzing potential trade-offs between different sustainability aspects.

Alternative Use Cases

Lastly, in this project the main focus has been to implement the design in an office context. The proposed solution has the potential to fit a wider range of contexts such as hospitals, nursing homes, waiting rooms, schools and educational institution, shopping centers, or even at home. There is an opportunity area to approach a larger market segment, thereby the chance for success.

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