# Reducing the indoor exposure to traffic emissions:

## Study and concept design of air purification systems for the façades of high-rise buildings in industrialized urban environments

# Colofon

**Title**
Reducing the indoor exposure to traffic emissions: Study and concept design of air purification systems for the façades of high-rise buildings in industrialized urban environments

**University**
Technical University of Delft
Faculty of Architecture & the Built Environment
Master track: Building Technology

**Tutors**
M. (Marcel) Bilow
E. R. (Eric) van den Ham

**Board of examiners Delegate**
T. E. (Tuuli) Jylhä

**Student**
D. J. (Daniel) van der Helm

**Student number**
4160398

**Contact**
d.j.vanderhelm@gmail.com

**Date**
04 / 11 / 2021

# Definitions

| | |
|---|---|
| ***Aerosol penetration*** | Quantity of particles passing the filter |
| ***Air pollutant*** | The particle or gas that needs to be filtered out of the airflow because it is causing problems |
| ***Capture mechanism*** | The forces or chemical conversions that cause pollutants to be filtered from the air. |
| ***Charge density*** | The amount of electrostatic force per unit volume of an electret filter |
| ***Cold downdraught*** | the phenomenon of warm air cooling when entering the room and then "falling" down |
| ***Dust holding capacity*** | The amount of particulate matter that the filter can capture before the filter is saturated with dust |
| ***Face velocity*** | The wind speed at which the wind hits the front of the filter |
| ***Filter performance*** | The amount of a pollutant a filter removes, often expressed as a percentage |
| ***Filter quality*** | The amount of a pollutant a filter removes in relation to the pressure drop |
| ***Flow rate*** | The speed at which the air passes the filter or ventilation opening |
| ***Packing density*** | The amount of fibers per unit volume of a filter |
| ***Pressure drop*** | The air resistance caused by a filter or ventilation opening |
| ***Retention time*** | The time polluted air spends in the area of the filter where the capture mechanisms take place |
| ***Sick Building Syndrome*** | The term for the set of health complaints that building occupants say they experience and attribute to poor ventilation |
| ***Ventilation type C*** | A ventilation system that operates on the basis of natural supply and mechanical exhaust |

# Summary


The problem for which solutions are proposed in this report is ambient air pollution, which causes health risks for people living indoors worldwide. This research focuses on the two Major Air Pollutants nitrogen dioxide and particulate matter, that cause the most problems now and in the future.

The starting point of this research is to solve the problem within the building industry and with the use of natural ventilation. This distinguishes it from existing solutions in mechanical ventilation systems such as the HEPA filter. The purpose of this research is to add a new function to the façade by filtering the incoming air using existing air purification technologies and applying them in an innovative way.

The research focuses on high-rise buildings in urban areas in industrialized regions, because there the exposure to polluted air is mainly indoors. Despite the fact that in those regions other measures are or already have been taken to reduce air pollution, this is still not enough and in these regions the willingness to apply technological solutions in the building industry is high.
The focus is on a facade type that is fully or partially closed and placed in a building that uses ventilation type C, which means natural supply of air through the facade and mechanical exhaust within the building.

The research question answered is as follows:
*'How can the façade of a high-rise building in an industrialized region be designed to improve the indoor air quality by using ventilation type C?'*

An answer to this question is given in this research by six concept designs and two elaborations in two case studies of the building 'Montevideo' in Rotterdam, the Netherlands.
To obtain that answer, a literature study was carried out to examine existing air purification technologies, five of which were further elaborated and their relationship to each other determined. It was also investigated what has to be taken into account when designing ventilation openings. Hereby it was examined which ventilation openings are relevant for this research and how they relate to each other.
Partly to validate the literature, partly to discover how air purification technologies work and mainly to support the concept designs, a test set-up was made to test filters for filtering out particulate matter. A sub-goal was to do this with a test set-up at home instead of in a laboratory.
For this research, hard criteria have been formulated that the concepts must meet. Soft criteria have been defined in order to be able to compare the different concepts and determine which concept is best to be worked out in which case study.

The concept designs and case studies, which are answers to the main question were created to serve as inspiration for designers interested in developing facade systems that filter air. As such, the designs in this research are primarily conceptual examples and are not yet a product. This research provides a theoretical basis for further concepts to be developed and applied in case studies. In the recommendations a start has been made on how the designs of the case study could be further developed into concept designs.

# Table of content

# 1
# Introduction

- ***1.1 Context***
  The context of the research is presented with several news items.

- ***1.2 Problem statement***
  The problem statement is defined by researching the definition, sources, location, exposure, norms, consequences and trends of the problem.

  This can be summarized as:
  *Health risks due to high ambient concentrations of traffic related pollutants in urban areas and especially indoors. The most relevant traffic related pollutants for this research are particulate matter and nitrogen dioxide.*

- ***1.3 Objective***
  The objective that follows from the problem statement and the starting point of this research.

  This can be summarized as:
  *Finding new solutions for a façade of a building that reduce the indoor air pollution of nitrogen dioxide and particulate matter, by making use of existing air purification technologies and the natural air flow.*

- ***1.4 Focus***
  To narrow down the scope of the research the location, target group, façade type, building ventilation type and building regulations are defined.

- ***1.5 Research questions***
  In every chapter of this report several research questions are answered, which are presented in this paragraph.

  The main research question is as follows:
  *How can the façade of a high-rise building in an industrialized region be designed to improve the indoor air quality when ventilation type C is used?*

- ***1.6 Research methodology***
  The structure of this research and how the research is conducted is presented in this paragraph.

## 1.1 Context

Nowadays air pollution is still a hot topic and causes problems around the world. The issue is repeatedly discussed in the news.
A news item from The New York Times written by Bakalar (2020) has as title: “Air Pollution Takes a Global Toll on Heart Health”. In that article it is explained that 14 percent of all cardiovascular events and more than 8 percent of cardiovascular deaths are related to air pollution which is claimed by a study from Hystad et al. (2020). The World Health Organization says that 91% of the world population in 2016 was living in places where the WHO air quality guidelines levels were not met.
A lot of the problems seems to be in urban areas, when reading for instance an article from The Guardian, Butler (2020), that states that more than one in 19 deaths in Britain’s largest towns and cities are related to air pollution. Also the article of Ellis-Petersen (2020) claims that India’s capital, Delhi, often becomes the most polluted city in the world during its winter, due to smog and toxic air particles. Most of these problems are caused by air pollution with particulate matter.
The last example is from the Netherlands where a lot of the news items are more specific related to the pollution of the air with nitrogen dioxide, for instance the article presented in the Volkskrant by Hofs (2020). In that article it is made clear that nitrogen dioxide is a major problem for the natural environment in the Netherlands.
It seems that air pollution is still a problem all around the world and has consequences for the human health and the environment.

## 1.2 Problem statement

To define the problem the following questions are answered in this paragraph:

- *Definition: What is the problem about?*
- *Sources: What causes the problem?*
- *Location: Where does the problem exist?*
- *Exposure: Where are people exposed to the problem?*
- *Norms: How big is the problem according to the norms?*
- *Consequences: What are the consequences of the problem?*
- *Trends: How will the problem develop in the future?*

### 1.2.1 Definition

According to Kampa and Castanas (2008) an air pollutant is by definition any substance which may harm humans, animals, vegetation or materials. When those pollutants are emitted they become part of the ambient air, the atmospheric air in its natural state. When in this research air pollution is mentioned, the so called ambient air pollution is meant.
At the moment 3000 different air pollutants have been identified, according to the study of Fenger (1999). The impacts of only 200 of those pollutants have been investigated and for the ambient concentrations even less. From all those pollutants only a few, the so-called indicators or Major Air Pollutants (MAP) are defined, which are particulate matter, ozone, nitrogen dioxide and sulphur dioxide, according to the World Health Organization (2006). The Environmental Protection Agency (EPA) in the United States focuses their policy on even six pollutants; the four mentioned above with in addition carbon monoxide and lead.
Other air pollutants are for instance Volatile Organic Compounds, from which the most common are acetone, formaldehyde and benzene. Those are described in Fenger (1999) as Hazardous Air Pollutants (HAP).
Air pollutants mainly exist in two forms. The WHO speaks of the gaseous- and the particulate air pollutants. Kampa and Castanas (2008) states that the pollutants can be grouped into four categories: gaseous pollutants, persistent organic pollutants, heavy metals and particulate matter. The most pollutants can be categorized as primary pollutants which are particulate or gaseous matters that are released from sources like industries, automobiles and buildings. (Sakthivel, 2019, p.39).
The air pollutants where this report focuses on are nitrogen dioxide and particulate matter, these pollutants are therefore defined further.

***Nitrogen dioxide***

This is a reddish-brown gas that consists of an inorganic

compound of nitrogen ($N_2$) and oxygen ($O_2$), which together form nitrogen dioxide ($NO_2$). See figure 1.1 for an illustration of the molecule.
The most well-known problem caused by this gas is acid rain. According to European Space Agency (ESA), the Netherlands lies in one of the most heavily polluted areas on earth when it comes to nitrogen dioxide.

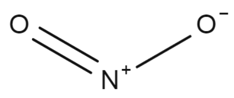



Figure 1.1 | Figure of a molecule structure of nitrogen dioxide | Source: (Gas Encyclopedia, 2021)

***Particulate matter***
First particulate matter was defined as Total Suspended Particulate matter (TSP), a name for all solid particles that are suspended in the ambient air. Later this definition is defined more based on the difference in particle size. The abbreviation commonly used now is PM. The number placed behind it indicates the maximum cross-sectional area of the particles in micrometers. So PM2.5 means particulate matter with a maximum particle size of 2.5 µm.

Also different categories have been defined as ultrafine particles which are smaller than 0,1 µm, fine particles which are smaller than 1 µm and coarse particles larger than 1 µm. The particle size is relevant since it determines the site in the respiratory tract of the human body where they will deposit. Usually the smaller the particle is the further it will penetrate into this respiratory tract. In figure 1.2 an illustration of different sizes of PM is given.

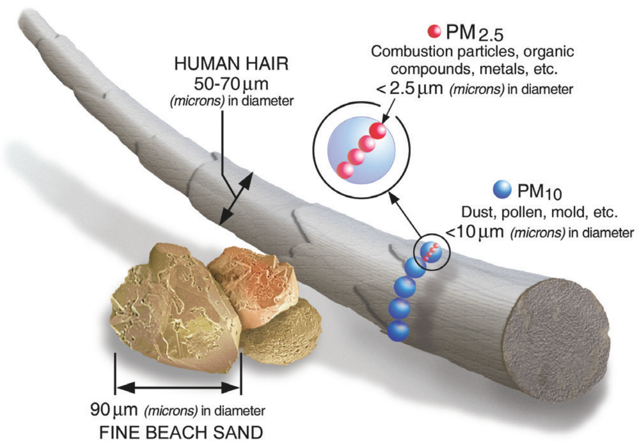



Figure 1.2 | Illustration of different sizes of particulate matter compared to a human hair and fine beach sand | Source: (EPA, 2021)

### 1.2.2 Sources
The common sources for anthropogenic air pollution are road transport, stationary combustion sources and industries. Besides that there are also natural sources like sea spray, desert and soil dust and pollen.
In general the main sources for the present air pollution levels in western cities are anthropogenic and traffic related (WHO, 2006, p.37). According to Kampa and Castanas (2008) the main anthropogenic sources are mobile and stationary combustion sources.
Also Fenger (1999) indicates in his research that the dominant sourse of urban air pollution is combustion in industry and in cars.
Nitrogen dioxide is created by the combustion process in the engine of a car. Nitrogen and oxygen are bind together when the motors heats up.
Particulate matter is a product of this combustion process and is also caused when small pieces of rubber wear off the tires.

### 1.2.3 Location
The problem of air pollution is a worldwide problem. How big the problem is depends mainly on two factors: the extent of development of a region and the density of the population.

According to Mayer (1999) the problem is often most severe in megacities in developing countries. An explanation for that is given by the research of Fenger (1999) who introduces a schematic presentation, see figure 1.3, of how urban air pollution levels are likely to develop in different regions with different levels of development.
When the development of a region increases, first the air pollution will increase too due to the increase of traffic and other emissions. After a certain development is reached, first measures are taken to control the emissions and later to improve the air quality itself until at the end the WHO guidelines are met.
In this perspective Africa and Latin America can be seen as the developing countries, Asia and the eastern part of Europe as regions where the economy is in transition and the rest of Europe, Australia and United States can be seen as industrialized regions, according to the research of Fenger (1999)

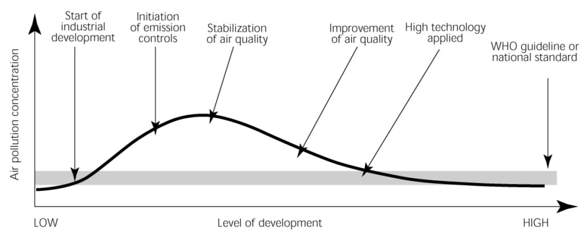



Figure 1.3 | Schematic presentation of how the urban air pollution levels are likely to develop according to the level of development of the region | Source: (Fenger, 1999)

### 1.2.4 Exposure

How people are exposed to the problem depends on how developed the region is. Regarding the exposure the WHO found out that most of the population in the developed countries is exposed to air pollution in the urban indoor, while most of the population in the developing countries in the rural indoor and rural outdoor, see figure 1.4.
Riley et al. (2002) also states that most people come into contact with particulate matter indoors.

Air pollution can enter the home through the ventilation system or can originate inside the home itself. In developed countries the pollutants enter mainly through the façade, while in developing countries there are also some indoor pollutants that arise when more primitive methods of cooking and heating are used. Worldwide, people are increasingly living in urban areas. This trend is increasing people's exposure to air pollution, especially indoors.

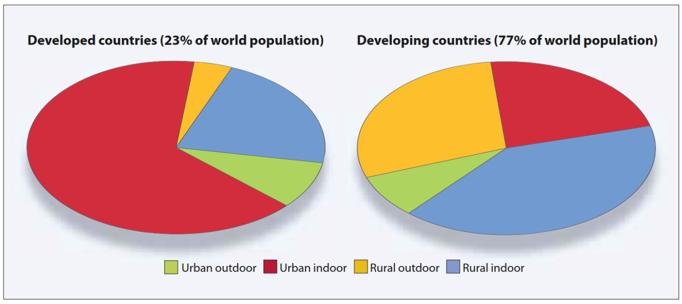



Figure 1.4 | The exposure of people to air pollution divided into four microenvironments. The situation in *developed* countries is compared with the situation in *developing* countries | Source: (WHO, 2006)

### 1.2.5 Norms

Organizations, such as the World Health Organization (WHO) and the Environmental Protection Agency (EPA) in the United States and the Air Quality Standards set by the European Commission, form the basic reference to determine whether a concentration of a pollutant in the ambient air is too high.
When the concentrations of pollutants in certain regions or cities are known they can be compared to the guidelines to see whether they are exceeding the guidelines.

More than 90% of the world is exposed to values of particulate matter which exceeds the guidelines of the WHO. The annual average concentration of PM10 varies from 20 to 220 µg in cities. Regarding PM2.5 in Asia the annual average levels are more than 80 µg/m$^3$, in Africa around 50 µg /m$^3$ where in Europe and America it is around 15 µg/m$^3$. The guidelines of the WHO are max 10 µm/m$^3$ PM 2.5 as annual average and max 20 µg/m$^3$ PM10 as annual average. (WHO, 2006)
Nitrogen dioxide seems to be a problem everywhere since the annual average concentration varies from 11 to 82 in cities while the WHO guideline is set to max 40 µg/m$^3$ as annual average.

### 1.2.6 Consequences

A lot of factors play a role in the impact that air pollution has on the human health. The exposure time, exposure to a mixture of pollutants rather than a single pollutant, the dose and the time of exposure are the factors to take into account. (Kampa and Castanas, 2008).
The effect on the human health can vary from nausea, difficulty in breathing, skin irritation, birth defects, reduced activity of the immune system and to cancer. The health effects can mainly be distinguished to acute, chronic not including cancer and cancerous.
The primary systems in the human body that are affected are mainly the cardiovascular- and the respiratory system, but also the nervous-, urinary- and the digestive system can be affected. (Kampa and Castanas, 2008)

As far as particulate matter is concerned, the finer the particles are, the further they penetrate into the respiratory system and the more harmful they are to health as a result. This was shown in a study by Xing et al. (2016) on the harmfulness of particulate matter to human health.

When considering the effects of nitrogen dioxide on the human health and the environment it can be stated that NO2 can damage the human respiratory tract and in case of long-term exposure it can even cause chronic lung disease.
High levels of nitrogen dioxide are also harmful to vegetation and can damage materials in the built environment such as furnishings and fabrics.

### 1.2.7 Trends

Since the urban atmosphere in most cities is dominated by traffic emissions, the air pollutants to control are now mainly the nitrogen oxides, the whole spectrum of the organic compounds (VOCs) and the particulate matter. Emissions from industry and space heating are getting less and less relevant, especially in industrialized countries (Fenger, 1999).
The amount of traffic exhaust emissions will be reduced in the future due to the growth in the use of electric cars. This is especially the case for emissions like nitrogen dioxide and VOCs. However, the emissions of particulate matter will still be a concern since cars produce also a lot of particulate matter with their tiers instead of only their combustion motors.
These so called non-exhaust emissions are researched by Timmers and Achten (2016). They found that there is a positive relationship between vehicle weight and non-exhaust PM emissions. Since electric vehicles are like 24% heavier than the conventional cars, PM emissions

from electric vehicles are therefore comparable to the PM emissions of conventional cars.

### 1.2.8 Problem statement

The problem statement of this research is as follows:

*Health risks due to high ambient concentrations of traffic related pollutants in urban areas and especially indoors. The most relevant traffic related pollutants for this research are particulate matter and nitrogen dioxide.*

***Sub problems***

The sub problems are indoor health risks that are caused by other air pollutants such as VOCs, $SO_2$ and ozone. Carbon dioxide is not directly a thread to the human health, but is also relevant regarding the greenhouse effect.

## 1.3 Objective

The starting point of this research is to find solutions to the problem within the building industry. In many buildings, measures have already been taken to combat air pollution. The most well-known are the HEPA filters in mechanical ventilation systems.
This research distinguishes itself by focusing on techniques that make use of the natural air flow through the facade. Examples are already known such as a window ventilation grille filter. This research attempts to investigate more existing filter technologies to discover how they can be integrated into the facade and how this can be used to develop new systems that do not yet exist.
In this way, this research tries to add the function of filtering the air to the pallet of functions that a facade often already has, as shown in figure 1.5.

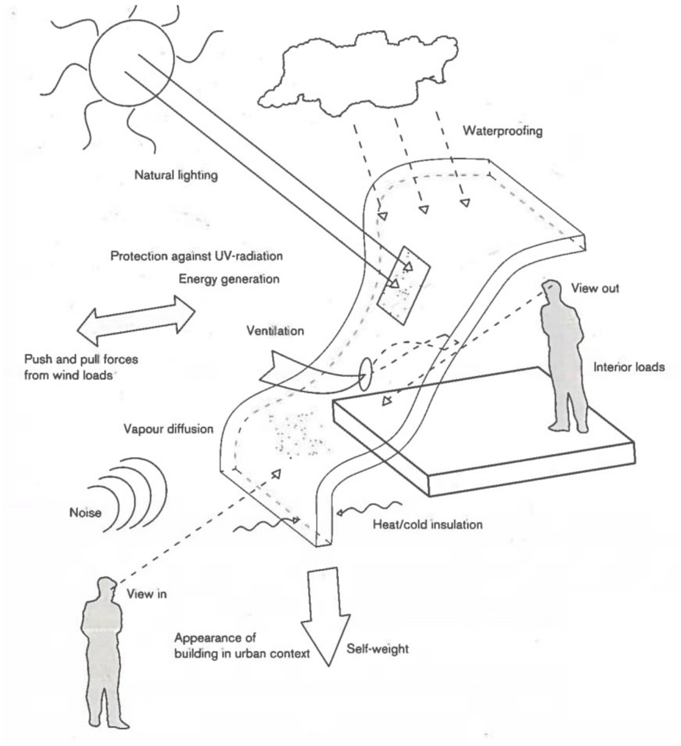



Figure 1.5 | The various functions that a facade structure can perform. In this research, the function of air filtering is added to it | Source: (Knaack et al., 2007)

### 1.3.1 General objective

The objective of this research can be summarized as follows:

*Finding new solutions for a façade of a building that reduce the indoor air pollution of nitrogen dioxide and particulate matter, by making use of existing air purification technologies and the natural air flow.*

***Sub objective***

The sub-objective of this research can be summarized as follows:

Purification of one of the other Major Air Pollutants

- Implementation of other façade functions
- Being a sustainable solution
- Being an aesthetic solution

### 1.3.2 Final products

The main end products that follow from this research are the *six concepts*, as presented in chapter eight. These concepts reflect the theory explored in chapters two through five. These concepts can serve as inspiration to conduct further research and develop a facade product.

How a concept can be used as a basis for a facade design was carried out in *two case studies*. These constitute the second major result of this research.

## 1.4 Focus

To narrow down the scope of the research the location, target group, façade type, building ventilation type and building regulations are defined.

### 1.4.1 Location

The location where the product is designed for, determines several boundary conditions such as the building regulations, the climate conditions and the willingness of the people for the product.

For this research the Netherlands are chosen to use as reference country. This country has a high level of development, has a high political willingness regarding measures to reduce air pollution and has a building market that is likely to invest in air filtering technologies. Also the problem of nitrogen dioxide is a hot topic at the moment in the Netherlands and therefore it is urgent to reduce nitrogen dioxide from the air. At last the Building Regulations are quite strict and complete, which means if the construction is allowed to build here it might be allowed to build elsewhere too.
More specifically the city of Rotterdam is selected as reference city for this research. It is a city in the Netherlands where a lot of new high-rise are being built, where air pollution is an issue due to the emissions from traffic and the industries in the harbor and were people are the most interested in innovative solutions.

### 1.4.2 Target group

For a product like this several target groups can be expected, such as residences, companies, utility buildings and public buildings. The more the user of the building is exposed to the inside air the more benefit the user has from the air purification technique. It is therefore less obvious to focus on the utility or public buildings since it is less clear who is going to profit from the investment of the air purification system. Residences are a more logical choice since people spend a lot of time at home and it is clear who benefits from the investment. A company can also be a candidate for this system, especially when the company attaches great importance to the well-being of their employees.

The target group in this research are residents in the city of Rotterdam that live in a residential high-rise building. The reason for this is that those people really benefit from having such a quality improvement added to their livings and it is likely that there is a market for this.

### 1.4.3 Building type

A high-rise building seems to be a clever choice since the most technical issues are involved and since the building has a large façade surface which makes it possible to standardize the product and to create a decent enough effect. Also the wind speeds are relatively high, which are useful when using the natural air flow for the system.

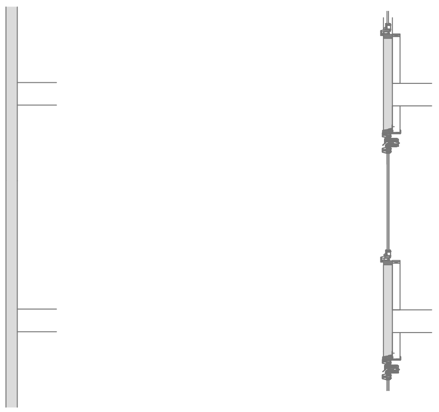


Figure 1.6 | Example of facade type A (left image) and facade type B (right image) | Source: own work

### 1.4.4 Facade type

The solutions in this research are created for closed facades and partly closed facades with windows.
In this research a completely closed façade is called façade type A, as illustrated in figure 1.6.
A half-open façade is in this research façade type B

### 1.4.5 Ventilation type

In this research the focus lies on how to filter the outside air in the natural air flow that enters the building. Four different principles are possible in buildings, type A, B, C or D.

Type A is a ventilation type with both a natural air supply and a natural air exhaust. This ventilation type is not allowed anymore in the Netherlands, due to the unhealthy conditions it can cause and also because the temperature differences between outside and inside can be too large. This ventilation type is therefore not relevant for this research.
In ventilation type B is system with a mechanical supply and a natural exhaust. This type is not used often in modern buildings anymore.
Ventilation type C is the opposite of type B having a natural supply and a mechanical exhaust. This is a desired ventilation type since this system crosses out the negative effects of natural ventilation by adding positive effects with the use of the mechanical exhaust. The main disadvantages of this system are heat loss and that the air is not filtered before entering the building. If those factors can be improved this ventilation type can be very efficient because it doesn't need that much maintenance and energy as system D does.
Ventilation system D where only mechanical ventilation is used is not the scope of this research. For mechanical ventilation systems there are already plenty of air purification systems on the market such as HEPA filters inside the ventilation ducts. Also ventilation type D has two big disadvantages that the user loses the connection to the direct outside world and that this system uses a lot of energy.

In this research the focus lies on how to design air purification technologies for buildings with ventilation type C. The main reasons for this are that ventilation type C is a more sustainable alternative for ventilation type D and that there is still much potential to research innovative air purification solutions for this type of ventilation.

### 1.4.6 Building regulations

The building regulations form the boundary conditions for the system regarding the safety, noise, heat and cold and other technical issues.
For this research the Dutch building norms are used as reference, which are combined in the so-called 'Bouwbesluit'.

## 1.5 Research questions

### 1.5.1 Main research question

The main research question of this research is as following:

*How can the façade of a high-rise building in an industrialized region be designed to improve the indoor air quality when ventilation type C is used?*

### 1.5.2 Sub research questions

Based on the, objective of this research, the main research question and the direction of solutions several more specific questions can be asked. In the following listing the sub questions are presented per Chapter.

#### Literature research

***Chapter 2***

*Which air purification technologies form the basis of this research?*
- *What are the capture mechanisms of the air purification technologies that form the basis of this research?*
- *What are the most important properties of the air purification technologies that form the basis of this research?*

***Chapter 3***
- *How can the different technologies be compared to each other?*

***Chapter 4***
- *Which conditions must be taken into account when designing ventilation openings?*
- *Which ventilation openings are relevant for this research?*
- *How do the different ventilation openings relate to each other?*

#### Validation

***Chapter 5***
- *Is it possible to test filters at home for their per formance and pressure drop?*
- *How can the test results support the design?*

#### Boundary conditions

***Chapter 6***
- *What are the hard criteria that the design must meet?*
- *What are the soft criteria with which the con cepts can be tested?*

#### Concept design

***Chapter 7***
- *How did the different concepts develop?*
- *How do the different concepts relate to each other?*

#### Case studies

***Chapter 8***
- *How can the concept 'Outside filter box variant I' be developed further for the case of renovating a part of the facade of the Montevideo in Rotterdam?*

***Chapter 9***
- *How can the concept 'Active Green Wall' be developed further when a new design for a part of the facade of the Montevideo in Rotterdam is considered?*

## 1.6 Research methodology

Chapters two through five describe the literature review. This provides the theoretical basis for developing the concepts and testing them.
Chapter six, validation, explains how tests were conducted on existing filters and building materials. These tests verify findings from the literature and test the operation of concepts to the extent possible with the test setup. Also listed here are the results of a test done to further develop a concept in the case study.
Chapter 7, boundary conditions, describes the framework within which the concepts were designed. Also described here are the design criteria used to analyze the concepts.
Chapter eight, concept development, describes how the concepts were created.
Chapter nine describes the case study. Here, a concept was chosen from the list of concepts, which was further elaborated to the needs of the case study.
Based on this elaboration in the case study, several recommendations were formulated, which are included in the last chapter.
Figure 1.7 shows the structure and coherence of the study schematically.

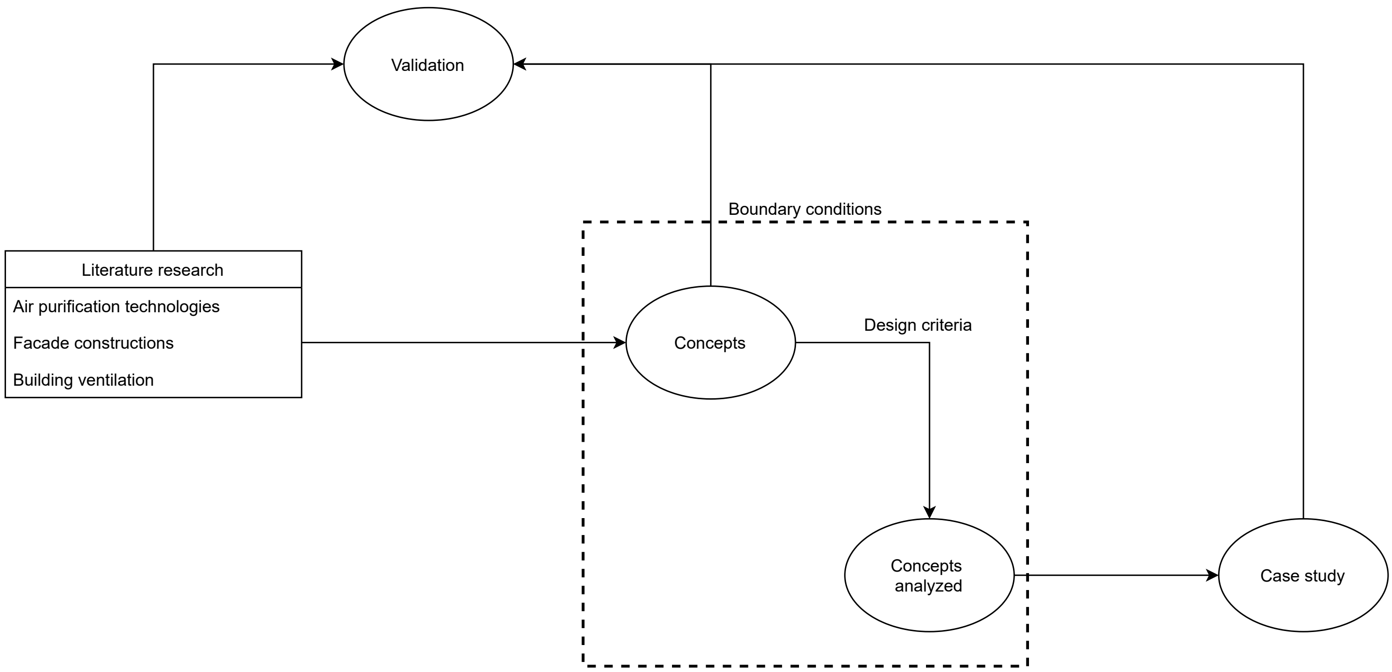



Figure 1.7 | Schematic overview of the structure of this research | Source: own work

# 2
# Literature review: Air purification technologies

- ***2.1 Selection of air purification technologies***
  A selection of air purification technologies based on three criteria is presented in this paragraph answering the following question:

  ***'Which technologies form the basis of this research?'***

- ***2.2 Capture mechanisms***
  The most relevant capture mechanisms are explained in more detail answering the following question:

  ***'What are the capture mechanisms of the air purification technologies that form the basis of this research?'***

- ***2.3 Explanation of several important properties regarding air purification technologies***
  In this paragraph the following question is answered:

  ***'What are the most important properties of the air purification technologies that form the basis of this research?'***

## 2.1 Selection of air purification technologies

Based on the fact that there are mainly two types of emissions, the particulate emissions and the gaseous emissions, there are also two types of emission- reduction techniques, which are particulate-purification techniques and gas-purification techniques or a combination of those two.
A lot of air pollution purification technologies are based on technologies that are used in the industry, such as industrial exhaust gas and related gas treatment technologies. According to Liu et al. (2017) these technologies can be mainly classified into three categories: dust removal, gas purification and sterilization technologies. Sterilization technologies are not the focus of this research and are therefore not included in the research.

The three main criteria on which air purification technologies were chosen are whether they filter the right pollutant, whether they can function at a low pressure drop, and whether they are applicable in a facade.

| Pollutant category | Pollutant | Technology | Type |
|---|---|---|---|
| Gas | VOCs | Cryogenic condensation | |
| | SO2 | Lime absorption | Semi-dry<br>Dry |
| | VOCs (no NOx) | Ozonation | |
| | VOCs (NO2) | **Photocatalytic oxidation (PCO)** | With TiO2 catalyst |
| | VOCs | Scrubber | Spray tower<br>Jet scrubber<br>Venturi scrubber |
| | VOCs (no NOx) | UV photolysis | |
| Gas and particulate matter | VOCs (mainly)<br>PM | Adsorption | Activated carbon filter |
| | VOCs (mainly)<br>PM | **Biofiltration** | **Passive** |
| | VOCs<br>PM (mainly) | **Biofiltration** | **Active filter** |
| | VOCs (produces NOx)<br>PM | Non-thermal plasma (NTP) | |
| Particulate matter | PM | Mechanical filtration | Ceramic filter<br>**Cyclone separator**<br>**Dynamic insulation**<br>Fibrous filter<br>Inertial impaction filter<br>Sedimentation chamber<br>Transparent filter |
| | PM | Electronic filtration | **Electret filter**<br>Electrostatic precipitator (EPS) |

Table 2.A | Summary of most of the existing air purification technologies ordered by which pollutants they filter. The ones that are selected for this research are highlighted | Source: own work

### 2.1.1 Pollutant

Table 2.A gives a summary of the most commonly used air purification technologies in either the industry or the building environment. The table is ordered by the three pollutant categories: gas, gas and particulate matter and only particulate matter. It is also made visible which technology filters which pollutant.
Several of the technologies are not relevant for this research because they don't filter particulate matter or nitrogen dioxide. For instance lime absorption, ozonation, UV-photolysis, adsorption with activated carbon filter and non-thermal plasma are therefore not relevant for this research.
The technologies that are highlighted in the table are relevant for this research.

### 2.1.2 Pressure drop

An overview of which technologies function at a high or low pressure drop and whether the technology requires mechanical or natural airflow is shown in table 2.B.
For those technologies where both high and low pressure drop are shaded in the table, the pressure drop depends mainly on the characteristics of the technology and how the technology is applied. The technologies shown in bold in the table are suitable for further investigation.

| Technology | Type | High pressure drop / mechanical air flow | Low pressure drop / natural air flow |
|---|---|---|---|
| Activated carbon filter | | ■ | |
| Electrostatic precipitator | | ■ | |
| Ceramic filter | | ■ | |
| Fibrous filter | HEPA | ■ | |
| | ULPA | ■ | |
| | Medium | ■ | |
| | **Coarse** | | ■ |
| Ozonation | | ■ | |
| UV photolysis | | ■ | |
| **Inertial impaction filter** | | ■ | ■ |
| **Cyclone filter** | | ■ | ■ |
| **Biofiltration** | | ■ | ■ |
| **Dynamic insulation** | | ■ | ■ |
| **Photocatalytic oxidation (PCO)** | | | ■ |
| **Sedimentation chamber** | | | ■ |

Table 2.B | Overview of which technologies require a high pressure drop and mechanical air flow and which technologies can also perform at a low pressure drop and natural air flow | Source: own work

### 2.1.3 Application in facade

Technologies that are not likely to use in a façade are cry-condensation and scrubbers. The first one requires the air flow to be at very low temperatures and the latter is a technology that is too complex and physically too large to implement in a façade.
Most technologies can be applied to a facade with some modification, where they can efficiently filter particulate matter and $NO_2$ to a greater or lesser extent.

The capture mechanisms that are relevant for this research are: *electret filter, inertial impaction filter, cyclone filter, biofiltration, dynamic insulation* and *PCO.*

## 2.2 Capture mechanisms

Every technology works according a certain capture mechanism or combines multiple mechanisms at the same time. Therefore it is important to explain first which capture mechanisms form the basis for the technologies.

A lot of capture mechanisms for gases are based on creating chemical reactions with the gas to form less harmful products, such as microbiotic oxidation, chemisorption and photo catalysis.
To capture particulate matter mechanical and electrical capture mechanisms are used mostly, such as direct interception and electrostatic attraction.
In table 2.C the relevant technologies and types as mentioned above are ordered according to different capture mechanisms.

| | Capture mechanism | Technology | Type |
|---|---|---|---|
| Chemical | Adsorption | Activated carbon | |
| | Chemisorption | Lime absorption | Semi-dry<br>Dry |
| | Microbiotic oxidation | Biofiltration | Passive |
| | Oxidation | Ozonation | |
| | Oxidation<br>Sterilization | UV photolysis | |
| | **Photocatalytic oxidation (PCO)** | **Photocatalytic oxidation (PCO)** | **Catalyst: TiO2** |
| Electrical | **Electrostatic attraction** | **Electret filter**<br>Electrostatic precipitator | |
| Mechanical | **Brownian diffusion** | **Biofiltration** | **Passive** |
| | **Direct interception** | Activated carbon<br>Biofiltration<br>Ceramic filter<br>**Dynamic insulation** | Active |
| | | **Fibrous filter** | HEPA<br>ULPA<br>Medium<br>**Coarse** |
| | | Transparent filter | |
| | Gravitational diffusion | Sedimentation chamber | |
| | **Inertial impaction** | **Cyclone separator**<br>**Inertial impaction filter** | |

Table 2.C | Technologies ordered by the dominant capture mechanism. The capture mechanisms that are relevant in this research are highlighted. | Source: own work

The capture mechanisms which are the most relevant for this research are *photocatalytic oxidation, electrostatic attraction, direct interception* and *inertial impaction*, because they are the most dominating capture mechanism of the technologies that are relevant for this research.
A summary of which factors, forces and phenomena are playing a role in the different capture mechanisms is presented in table 2.D.

| Capture mechanisms | | Factors that play a role |
|---|---|---|
| Direct Interception | Mechanical forces | Van der Waals force |
| | | Lift force |
| | | Gravitational force |
| Inertia | | Drag force |
| | | Centrifugal force |
| Diffusion | Diffusion forces | Thermophoresis |
| | | Molecular drift |
| | | Turbulent diffusion |
| | | Brownian diffusion |
| | | Gravitational force |
| Electrostatic attraction | Electrical forces | Coulomb force |
| | | Polarization force |
| Adsorption | Physisorption | Van der Waals force |
| | Chemisorption | Covalent bonding |

Table 2.D | This table gives a summary of the different capture mechanisms and how they are related to different forces, factors and phenomena that play a role | Source: own work

### 2.2.1 Brownian diffusion

This mechanism occurs mainly with particles smaller than 1 µm and benefits from low wind speeds. It is a mechanism where the particles no longer follow the main air stream, but follow their own random path determined by a collection of factors caused by molecules in the air.

### 2.2.1 Direct interception

Direct interception occurs when a particle follows the air flow and in the process comes close to a filter fiber and collides with or is attracted by the fiber. Typically, the particle is attracted enough to stick when it passes the fiber at a distance of up to one particle diameter. See figure 2.1 for a schematic illustration. The force that causes particles to stick is the Van der Waals force. How well this force acts on different particles depends on the material of the fiber.

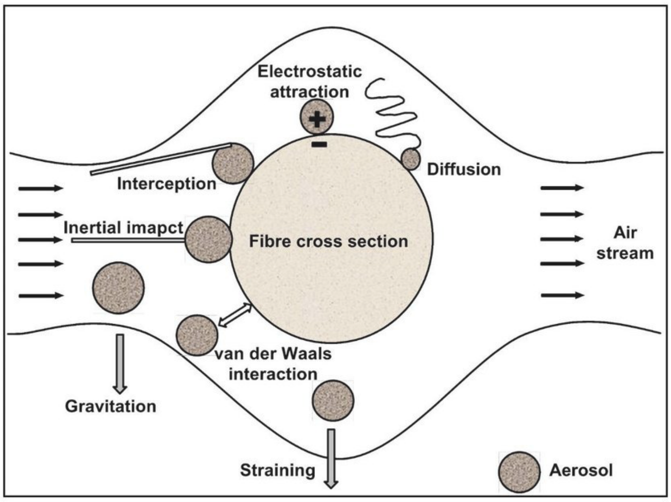



Figure 2.1 | Illustration of several particle capture mechanisms of a single fiber that play an important role in air purification technologies | Source: (Kadam, 2018, p.16)

### 2.2.3 Electrostatic attraction

Particles can be attracted towards a fibre or filter element with the use of electrical charges. When a particle has a negative or positive electric charge it is attracted

by filter elements with an opposite charge with the so called coulomb force.
Permanently charged fibers in an electret filter create a strong inhomogeneous electrostatic field which captures both charged and uncharged particles and let them stick onto the fibers. The charged particles are captured by Coulomb forces and the uncharged particles are polarized first inside the inhomogeneous field before they are captured by the fibers. In figure 2.2 those forces are schematized, according to the research of van Turnhout et al. (1981).

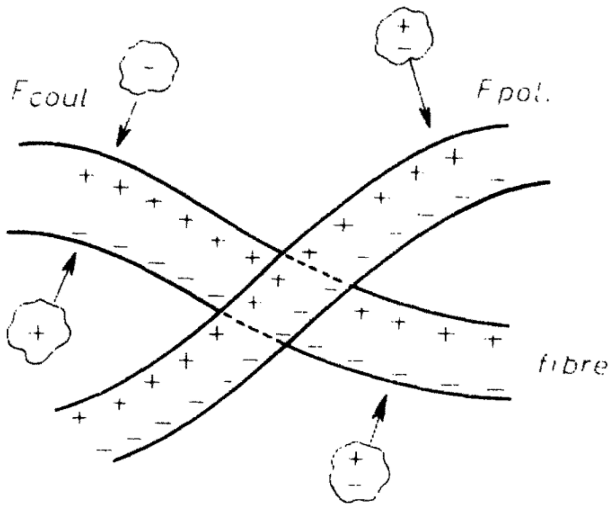



Figure 2.2 | Illustration of two ways in which an (un)charged particle can be attracted to a precharged fibre. On the left the particles are already charged and are therefore attracted with the Coulomb force. On the right the uncharged particles are depolarized in the electrostatic field first and are then attracted to the fibers with polarization force | Source: (van Turnhout et al., 1981)

### 2.2.4 Inertial impaction

Particles tend to follow the air flow, especially if the airflow is laminar and goes into one straight direction. When there is an obstacle, such as an filter fiber, the air flow changes it's direction to avoid the fiber and move along it. This change in direction causes drag forces on the particles in the air flow. Depending on how much momentum the particle has, the particle tent to move with the streamline and avoid the fiber or the particle follows (mostly) its initial path and collides with the fiber. The particles will then stick to the surface due to Van der Waals force.

The momentum of the particle can be described with the formula:

$$\bar{p} = m * \bar{v}$$

Where m is the mass of the particle and $\bar{v}$ the vector of its velocity.
The more the momentum of the particle has to change in either the magnitude or the direction, the harder it is for the particle to follow the streamline of the air flow and the simpler it is to follow its own trajectory. So when the velocity of the particle changes a lot in either the magnitude or the direction, it is likely that the particle follows its initial path.
From this formula it can also be concluded that when the mass of this particle is big, the momentum of the particle must be big too. Bigger particles are therefore more likely to follow their initial path than smaller particles and smaller particles are therefore harder to capture with inertial impaction.

Whether a particle follows its initial path or not is determined by the Stokes number. If Stk >> 1: particles with large Stokes numbers are dominated by its inertia and will continue along its initial trajectory, detaching from the air stream especially where the flow decelerates abruptly. If Stk << 1: particles follow the fluid streamline closely. How the Stokes number can be calculated is presented in sub paragraph 2.3.6 in the next paragraph.

### 2.2.5 UV-irradiation

UV radiation in sunlight can convert VOCs and $NO_2$ in the air into less harmful substances. According to Kang et al. (2018), one of those mechanisms is *photolysis*.
When the process of photolysis involves the use of a catalyst, it is also referred to as *photocatalysis*. These mechanisms are briefly explained here.

***Photolysis***
In photolysis, harmful substances such as $NO_2$ in the air are converted into less harmful substances. This mechanism is based on chemical redox reactions with dioxygen in the air, which only work under the presence of UV-light. The resultants of these redox reactions then react with the pollutants in the air and form less harmful products such as $H_2O$ and $CO_2$.

***Photocatalysis***
To let photolysis make a significant difference to air quality, it can be accelerated using a catalyst. Photolysis in combination with a catalyst is called *photocatalysis*. An important property of the catalyst is that it does accelerate the filtering process, but in doing so it does not consume itself. The catalyst is the basis of this technology.

According to Sakthivel (2019) several catalysts have been widely used and studied regarding photocatalysis. Examples of that are zinc oxide (ZnO), cadmium sulphide (CdS), zeolite and dolomite. However, the best option seems to be *titanium dioxide* ($TiO_2$), since this catalyst has a high selectivity for the air pollutant $NO_2$ and other air pollutants like $SO_2$, VOCs and CO, which are a sub-objective of this research.
According to Etacheri et al. (2015) $TiO_2$ has also improved chemical stability and a high oxidation potential in

comparison with other photocatalysts. In the research of Hashimoto et al. (2005) it is claimed that $TiO_2$ is the most efficient catalyst with the highest stability and lowest cost. It is also a safe construction material for humans and the environment. It is because of all those reasons that this research focuses on Photocatalysis with Titanium dioxide (PCO with $TiO_2$).

Under the presence of UV-light the Titanium dioxide is used as catalyst to generate electron-hole pairs. The outside air diffuses around the catalyst and the electrons have enough energy to move freely and participate in redox reactions with the dioxygen in the air. The resultants of these redox reactions then react with the pollutants such as $NO_2$ and form less harmful products such as $H_2O$ and $CO_2$.
This process is described more in detail in the thesis of Saktthivel (2019).

## 2.3 Explanation of several important properties regarding air purification technologies

In this section, the main properties of air purification technologies are explained in detail. This information is used in this study to correctly compare the technologies with each other. It also provides information on how the technologies can be applied correctly.

### 2.3.1 Dust holding capacity

Almost every filter needs to be cleaned after it has collected a certain amount of dust particles or dust. The dust collection capacity of the filter provides an indication of the time before a filter needs to be cleaned. This is an important value when considering the maintenance frequency of a filter.
This value can be estimated using the following formula:

$$\tau(h) = \frac{H * A}{0.01 * E * C * F}$$

with:
H: dust holding capacity [g/m$^2$ ]
A: surface of filter [m$^2$]
E: efficiency [%]
C: density of pollution in the air [g/m$^3$]
F: volumetric flow rate [m$^3$]

### 2.3.2 Performance

The performance of the filter indicates how well the filter is able to filter the relevant pollutant particles from the air stream and can be determined based on three factors:

- Aerosol penetration: how many particles pass
- the filter.
- Filter quality: how much is filtered in relation to pressure drop (explained in next sub paragraph)
- Most penetrating particle size: the size of the particles that pass the filter the most.

The aerosol penetration and most penetrating particle size should both be kept as low as possible and the filter quality as high as possible. In the case of gases only the first two factors play a role as there is no difference in particle size.

***Classification particulate filters***

The performance of the filters that filter particulate matter can be classified with the filter norm ‘ISO 16890’. In this norm a filter is placed in a group with a particle size of 1, 2.5, 10 or coarse, when the efficiency for that particle size is at least 50%. For instance a filter with ISO ePM2,5 70% means that the efficiency for filtering particles smaller than 2.5 μm lies between 70% and 75%,

rounded at 5%.
Figure 2.3 gives an overview of the four classes. ISO coarse filters can filter for instance sand and hairs, while ISO ePM1 can filter exhaust gases nanoparticles.


Figure 2.3 | Overview of the different filter classes for particulate matter and what type of particles they can filter | Source: (Robatherm, 2021)

Filters can also be classified with the letters G, M and F. Where G stands for coarse filters, M for ISO ePM10 and F for filters with ePM2.5 or higher.

### 2.3.3 Filter quality

The filter quality indicates how well a filter performs at a certain pressure drop. A filter that performs well can still have a low filter quality if the pressure drop is also very high. The formula for this is described in the study by Huang et al. (2013) and reads:

$$q_f = \frac{\ln \left( {}^{1}/_{P} \right)}{\Delta P}$$

Where P is the fraction of aerosol penetration and ΔP is the pressure drop across the filter.

### 2.3.4 Pressure drop

When air flow passes through an opening or a filter, the air undergoes resistance from this. This affects the air velocity negatively. If the air flow goes through a system with a high pressure drop, the air flow will be slowed down more than if it goes through a system with a low pressure drop. The pressure drop of a filter is therefore related to the reduction of the air speed that the filter causes.

The difference in wind speed of the air passing through an empty tube from the wind speed of the air in a tube with a filter gives the pressure drop according to the following formula:

$$\Delta P = \frac{\rho * (V_{FILTER} - V_{EMPTY})^2}{2}$$

with:
ΔP: Pressure drop [Pa]
ρ: Air Density [kg/m³]
v: Wind speed [m/s]

The pressure drop of a filter is determined by several factors, as described in Chapter three.

### 2.3.5 Flow rate

The wind speed through an opening can be described by the orifice equation:

$$Q = C_D * A * \sqrt{\frac{2 * \Delta P}{\rho}}$$

with:
Q: Air flow rate [m³/s]
CD: Discharge coefficient
A: Flow area [m²]
ΔP: Pressure difference across the opening
ρ: Air density [kg/m³]

The discharge coefficient is determined by the geometry of the orifice and the Reynolds number of the air flow. When assuming a turbulent air flow a CD = 0.8 is a good estimate according to a lecture by Dr. R. M.J. Bokel.

***In a filter***

The *Volumetric flow rate* is the volume of fluid or gas that passes through per unit time following the formula:

$$Q = v * A \, [\frac{m^3}{hr}]$$

with:
v: Air speed (m/s)
A: Area of the cross-section of the opening (m²)

The *Volumetric flow rate* plays an important role to determine the capacity of the filter, how much air it can process for a given period.

For every filter a certain optimal flow rate is required for which the filter performs the best. Some filter technologies benefit from a large flow rate, like the inertial impaction filters and other technologies benefit from a low flow rate like electret filters or photocatalytic oxidation.

### 2.3.6 Stokes number

The *Stokes number* is an indicator of how likely it is that a particle is dominated by its inertia and follow its initial trajectory or how likely it is that the particle will follow the fluid streamlines. This number is given by the formula:

$$Stk = \frac{t_0 * v_0}{l_0} \quad [1]$$

with:
$t_0$ : relaxation time
$v_0$ : fluid velocity well away from the obstacle [m/s]
$l_0$ : diameter of the obstacle [m]

The *Relaxation time* is given by the formula:

$$t_0 = \frac{\rho_p * d_p^2}{18 * \mu_0} \quad [2]$$

Where:
$\rho_p$ = particle density [kg/m3]
$d_p^2$ = particle diameter [m]
$\mu_0$ = dynamic viscosity [kg/m·s]

Substituting the formula for relaxation time in formula 1 gives:

$$Stk = \frac{\rho_p * d_p^2 * \; v_0}{18 * \mu_0 * l_0} \quad [3]$$

This number is important when determining whether a particle is dominated by its inertia or not and is trapped with an inertial impaction filter as explained in sub paragraph 2.2.4.

# Conclusion

- ***'Which technologies form the basis of this research?'***

  The air purification technologies that form the basis of this study were selected on the basis of whether they filter the right pollutant and whether they could be applied in a facade for practical reasons.

  Technologies for which references could easily be found in the built environment formed logical reasons for selection, such as *Bio-filtration* and *Fibrous filters*. Less common technologies were also selected, such as the *Cyclone separator* and *Photocatalytic oxidation (PCO)*.

  Technologies that are also interesting in this context, but were not examined further in this study are *Dynamic insulation* and the *Inertial impaction filter*.

- ***What are the capture mechanisms of the air purification technologies that form the basis of this research?'***

  Particulate matter and nitrogen dioxide are filtered out of the air by filter technologies in various ways. The main capture mechanisms can be divided into *chemical, electrical* and *mechanical* capture mechanisms.

  The five most relevant capture mechanisms are: *Brownian diffusion, Direct interception, Electrostatic attraction, Inertial impaction* and *UV-irradiation*, of which the working principle is explained and which forces and factors play a role.

- ***'What are the most important properties of the air purification technologies that form the basis of this research?'***

  The air purification technologies can only be compared with each other and applied in the right way if the main factors that play a role in the performance of a filter are explained. In this chapter, the following six factors are explained in more detail: *Dust holding capacity, Performance, Filter quality, Pressure drop, Flow rate* and *Stokes number.*

# 3
# State of Art: Air purification technologies and applications

In this chapter the basic information and the State of Art of the selected air purification technologies are presented. The research question in this chapter is as follows:

- ***How can the different technologies be compared to each other?***

First the technologies are presented and for every one of them the following sub questions are answered:

- *How is the technology applied in the building industry?*
- *What is the filter quality of the technology when applied according to the boundary conditions of this research?*
- *What factors influence the performance of the technology?*
- *How can the technology be constructed within the boundary conditions?*
- *How much maintenance does the technology require?*
- *What are the advantages and disadvantages of the technology when used within the boundary conditions?*

- ***3.1 Photocatalytic oxidation with $TiO_2$***
- ***3.2 Bio-façade: Living Wall System (LWS)***
- ***3.3 Bio-façade: Active Green Wall (AGW)***
- ***3.4 Cyclone separator***
- ***3.5 Fibrous filter: electret***
- ***3.6 Analysis***
Then the technologies are evaluated according to three criteria and are compared to each other

# 3.1 Photocatalytic oxidation with $TiO_2$

With UV irradiation, VOCs and $NO_2$ can be filtered via several processes, the most relevant process for this research being photocatalysis. This is a process in which pollutants such as $NO_2$ are converted into less harmful substances by means of chemical redox reactions with diogygen in the air under the influence of UV irradiation. This process is explained in more detail in paragraph 2.2.5..
A catalyst is used to speed up this process. Several can be used for this process, but this research focuses on the use of titanium dioxide ($TiO_2$).
This catalyst usually occurs in powder form as shown in figure 3.1.


Figure 3.1 | Photo of titanium dioxide in powder form, which can be bought in the webshop 'Ali Express' | Source: (Ali Express, 2021)

## 3.1.1 Application

Titanium dioxide is most commonly applied as a crystal form, with the so-called anatase form being the most stable. The best known product name on the market today is 'Degussa P25', according to Sakthivel (2019). It is a kind of granules or powder that can be incorporated into building materials or applied as a coating in various ways. The building materials or the object on which the coating is placed are necessary and form the so-called host of the catalyst.

In the research of Sakthivel (2019) a facade panel is designed on which PCO is applied.
The shape of the panel is optimized to increase the performance of the PCO, by maximizing the contact area of the $TiO_2$ with the polluted air and by increasing the retention time.
This resulted in a design with a whimsical shape, as presented in figure 3.2.

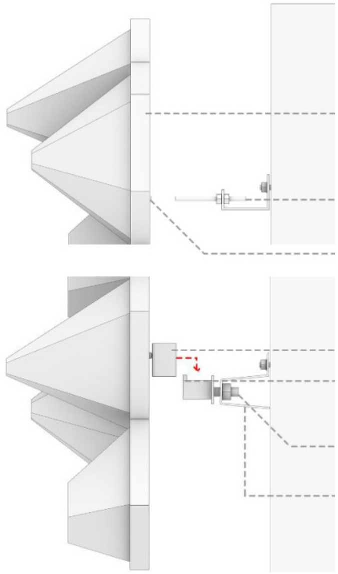


Figure 3.2 | Design of a facade panel on which PCO is applied | Source: (Sakthivel, 2019)

## 3.1.2 Filter quality

The filter quality indicates how well a filter performs at a certain pressure drop.

***Performance***

The performance of PCO with $TiO_2$ can be very different depending on how the technique is applied. In the study by Maggos et al. (2007), two types of paint containing nanoparticles of $TiO_2$ were tested. The mineral silicate paint converted 27% of the $NO_2$ in this test, while the paint type that consisted of styrene acrylic paint degraded as much as 71% of the $NO_2$ from the air with photocatalysis.

***Pressure drop***

This technology is often applied to a rough surface. The roughness of the surface determines how much the wind will swirl and be slowed down.
This results in a very low pressure drop. Usually the PCO coating is applied on the outside of the structure where the wind only flows along the structure and does not have to pass through an opening. Because of this and because the pressure drop is very low, it does not play a major role in this technology.

The filter quality of this technology is therefore mainly determined by the performance of the PCO with $TiO_2$.

## 3.1.3 Operating conditions

Several factors influence the performance of PCO with TiO2, the most important being the surface roughness of the host and the light intensity, but also the flow rate and relative humidity of the air play an important role. These are explained in more detail below.

### *Flow rate*
The reactions that take place in photocatalysis need time to take place. The slower the air flows past the catalyst the more likely the reactions are to take place and the more air is filtered. The surface roughness of the host can play an important role in keeping this flow rate low.

### *Surface roughness host*
How rough the material is on which the coating is applied affects the retention time and the total area where the coating is effective.
A rough surface causes air swirls, which has the effect of slowing down the airflow and therefore increasing the retention time.
A rough surface also means that the total surface area of the host increases and therefore that per square meter of host relatively more coating surface can be applied and more air comes in contact with the catalyst.
It is therefore better for the performance to use a material as host that has a slightly rough surface area.

### *Relative humidity*
The study by Maggos et al. (2007) investigated the effect of relative humidity on the performance of photocatalytic conversion of NOx. At relatively low concentrations of NOx in the air, as is the case with ambient concentrations of NOx entering a building, humidity has a negative effect on photocatalytic oxidation. This is mainly due to the fact that with a high humidity air flow, water droplets can be formed on the coating, which then forms a barrier between the coating and the air to be filtered.  Thus, the air should not be too humid to achieve high efficiency.

### *Light intensity*
At normal daylight intensities, such as 250 W/m2, the degradation rate of the photocatalysis is proportional to the light intensity, according to the research of Sakthivel (2019). Presence of direct solar radiation improves the photocatalytic degradation. When applying this technology in a facade, one should therefore take into account that the coating on the south facade will filter more air than the same panel on the north facade.

How much effect the difference in light intensity has on the performance of PCO depends on the application. Figure 3.3 shows five situations where PCO has been applied. For each situation, the façade oriented towards the north side has a worse performance. This is in the worst case a reduction of 80% and in the best case a reduction of 25%.

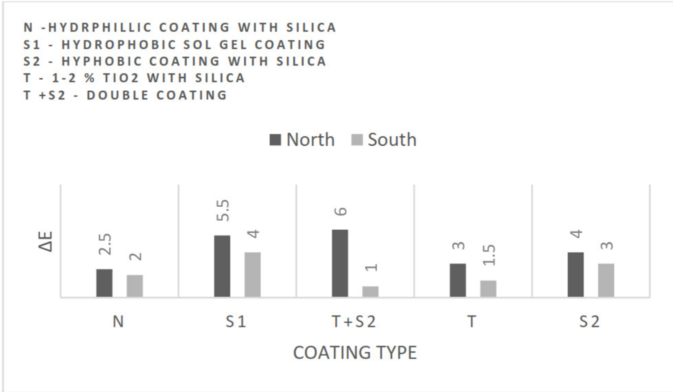



Figure 3.3 | Comparison of PCO applied to a south facade and a north facade | Source: (Sakthivel, 2019)

## 3.1.4 Construction and materials
Titanium dioxide occurs in a crystalline form, powder or grains, which can be applied to façade panels as *coating* or *embedded in the substrate*, depending on which material is used as host.

### *Coating*
By bonding $TiO_2$ to, for example, a silicate binder, a thin coating can be made. The advantage of a thin coating is that the proportion of $TiO_2$ that is used functionally is large. Almost all grains lie on the surface so they are in contact with the polluted air and in addition capture UV radiation.
In the study by Yang et al. (2006), a method is presented where they can apply a $TiO_2$ thin film to polymer substrates using a dip-coating process.

### *Embedded in substrate*
An example of this is when Titanium dioxide is mixed through cement. This can be done easily by adding the granules into the cement mixture. The cement can then be applied to the desired location and the TiO2 does not need to be applied separately.
The disadvantage here is that only the part of the TiO2 that lands on the surface of the mixture is functional, because only this part absorbs UV radiation and comes into contact with the polluted air. Thus, a large part of the TiO2 inside will remain unused.

### *Host materials*
Different materials can be selected as substrate on which the catalyst TiO2 can be placed. Sakthivel (2019) analyzed five materials for their advantages and disadvantages when using them as substrate. The materials concrete, quartz, glass, porcelain and ceramic tiles and thermoset plastics are selected from which the plastics and quartz have the best photocatalytic activity and need the least maintenance.
In the research of Chun et al. (2008) a coating of TiO2 is also used on metal, where it is also used as protector against corrosion.

*Color*
Titanium dioxide naturally has a white color. When used as a coating or when mixed into a host material it will cause a white color.

### 3.1.5 Maintenance
How much maintenance this technology requires depends on how it is processed and on which host material it is applied.
For example, polymer and quartz require the least maintenance and the acrylic paint examined in a case study in Sakthivel's research (2019) needs to be replaced 1x every 5 years.

Another phenomenon is the fact of accumulation of dirt on the coating. This dirt impedes the contact of the coating with the polluted air. Sakthivel (2019) indicates in his research that the coating should be washed at least once every two months. For this washing, rainwater flowing over the facade is also sufficient for this purpose.

### 3.1.6 Qualities
- The study by Kang et al. (2018) investigated for 27 VOCs how well they are filtered by UV irradi tion. Thus, in addition to NO2, other substances are also filtered
- Virtually maintenance-free
- Protects the substrate from UV radiation

### 3.1.7 Requirements
- UV irradiation can create by-products such as $CO_2$ and particulate matter, these have to be removed as well then (Kang et al., 2018).
- The relative humidity of the air shouldn't be too high since the performance of the $TiO_2$ will de crease then.
- The titanium dioxide should have access to enough light intensity to work efficiently.
- The wind speed should not exceed more than 1.5 m/s to keep the retention time long enough.

## 3.2 Bio-façade: Living Wall System (LWS)

A bio-façade refers to a green façade, where some form of planting is used in the façade construction. This technique is interesting for this research because plants can filter air. They can do this in different ways depending on how the air flows through the plants.
In this, based on the examples found, two types have been distinguished: systems in which the air only flows through the *leaves* and systems in which the air also flows through the *roots* of the plants. The first system is discussed in this paragraph and the second in paragraph 3.3.

In this variant of a bio façade, the leaves of the plants are used to filter the air. These plants can be placed on the façade whereby the air on the outside can flow past the plants uninhibited.
The particulate matter is filtered by various mechanisms. According to Ottelé, Haas, et al. (2011, p. 32) these are mainly inertial impaction and brownian diffusion.
With inertial impaction, the wind is changed in direction by the shape of the leaves, so that particularly the heavier particles will be deposited on the leaves. The rougher the leaf, the more vortices will be created, the more the wind direction will be changed and the more particulate matter will remain on the leaves.
When these vortices occur strongly and the air speed is reduced, brownian diffusion can also occur. In this effect, particulate matter particles collide with the leaves and stick to them. The lower the wind speed and the more vortices occur, the greater this effect will be. These capture mechanisms are further explained in section 2.2. 'Capture mechanisms'.

The nitrogen dioxide can be filtered in the pores of the leaves. According to Beerens et al. (2019), this gas can be filtered when it dissolves in the moisture contained in the leaves. The plant then converts it to oxygen.

### 3.2.1 Application
One way to achieve a green facade is a Living Wall System (LWS), as described in the study by Damen et al. (2014). These are systems where plants grow from a substrate that is part of a panel. This panel is then attached at a distance, with a cavity, from the main structure of the façade. Figure 3.4 shows a schematic example of such a LWS, which is based on the 'LivePanel' of the company 'Mobilane'.

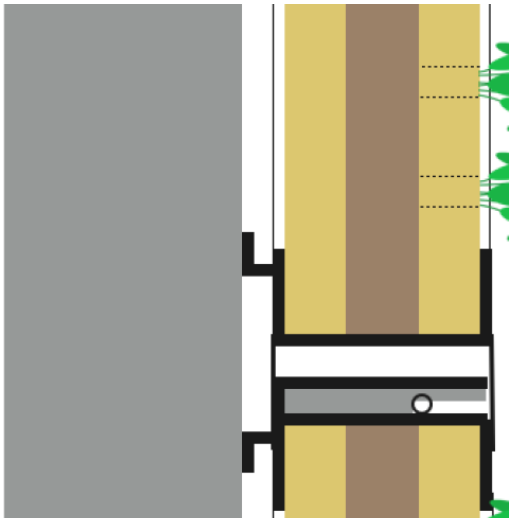


Figure 3.4 | Schematic example of a Living Wall System | Source: (Damen et al., 2014, p.72)

### 3.2.2 Filter quality

The filter quality indicates how well a filter performs at a certain pressure drop.

***Performance***

Based on two studies, it is possible to get an idea of the filter performance of a green facade where air flows through or past the leaves.
The study by J. Yang et al. (2008) gives an idea of how the air quality in an area can be improved by the application of green roofs. As much as 1675 kg of air pollutants were removed. Over a quarter of these were $NO_2$ and about 14% were PM10.
When the air flows past the leaves, according to a study by Steltman described in Ottelé, Ursem, et al. (2011, p.32) 20% of the particulate matter can be filtered out. Where the majority of the particulate matter consists of the fine and ultrafine, according to research by Ottelé et al. (2010).

***Pressure drop***

Since the airflow in this technology only passes through the leaves, the pressure drop is automatically low.

Despite this feature, the filter quality of this technology remains on the low side because the performance is also very low.

### 3.2.3 Operating conditions

The air purification performance of a bio-façade depends mainly on the *plant species* and to a lesser extent also on the *wind speed.*

***Plant species***

How well a plant filters has to do, among other things, with the roughness of its leaf surface and the density of its leaves. Each plant species therefore has its own typical performance.

***Wind speed***

Wind is needed first of all to allow the air to pass through the leaves, so the particulate matter and $NO_2$ come into contact with the leaves and are filtered.
Gentle wind is conducive to filtering via brownian diffusion and will provide better performance.
Strong winds can blow some of the particulate matter left on the leaves back into the air. This is described in Ottelé, Haas, et al. (2011, p.61) as the resuspension of particles due to the wind and this worsens the performance.

### 3.2.4 Construction and materials

A green facade can be constructed in several ways. The first important difference consists of whether the system is a ground-based system or a non-ground-based system. The ground-based systems can only be applied at limited height from ground level and are therefore not relevant for this study.

***Support system***

How the planting then uses the façade as a tool to grow upward is the second important difference in systems. Ottelé, Haas, et al. (2011) distinguish two systems: 'direct greening' and 'indirect greening'. In the first, plants grow directly on the main structure of the facade and in indirect greening, the plants use a sub-construction that is kept at a distance from the main structure of the facade with a cavity.

***Hydroponic system***

In a non-ground-based system, the plants grow from a growing medium in the facade, which according to Damen et al. (2014) can consist of potting soil, rockwool, substrate, or a geotextile.
Watering and fertilization will have to be done from a central irrigation system, which is almost identical for all non-grounded systems. In the research of Ottelé, Haas, et al. (2011), this technique is also called hydroponic systems. In this, the plants grow on a substrate that serves for the roots to have grip. The plants' nutrients are supplied through the water in the irrigation channels. Some substrates are designed to be able to retain moisture so that the plants always have access to the water and nutrients.
Types of substrate used in hydroponic systems are: rockwool, stonewool, vermiculite, perlite, coconut fiber, oasis cubes, sphagnum peat moss, rice hulls and polyurethane grow slabs.

***Five non-ground-based systems***

The study by Damen et al. (2014) distinguishes five categories of how a non-ground-based green facade can be constructed, illustrated in Figure 3.5.

Figure 3.5 | Schematic examples of five non-ground-based systems. From top to bottom: Geotextile systems, Panel systems, Tray systems, Combination systems and Continuous soil cores | Source: (Damen et al., 2014, p.60)

In a *geotextile system*, the plants adhere to a geotextile that is usually spread over a large portion of the façade and often placed directly on the underlying insulation layer.
Another system is a *panel system* in which the plants grow from a growing medium enclosed in a frame. These panels can be mounted from the factory directly on the facade with underlying cavity and insulation material. An example of a panel system is the *Living Wall System* presented in subsection 3.2.1.
The *tray systems* are similar to the panel systems but the plants grow vertically upwards from them instead of horizontally and the tray systems are placed directly on the façade structure and not separated by a cavity.
A *combination system* is one where trays are placed on the facade with a growing medium inside. Unlike the tray system, the trays are placed at a distance from the facade or possibly with a cavity between them.
The system with the *continuous soil cores* is similar to a geotextile system only this system has a thicker substrate layer.

***Living Wall Systems***

A Living Wall System is a form of a panel system. In this, four different types were then distinguished by Ottelé, Haas, et al. (2011), as shown in Figure 3.6. The type that uses mineral wool in the panel as a substrate to grow on served as inspiration for this research to develop the concept described in Section 7.2.

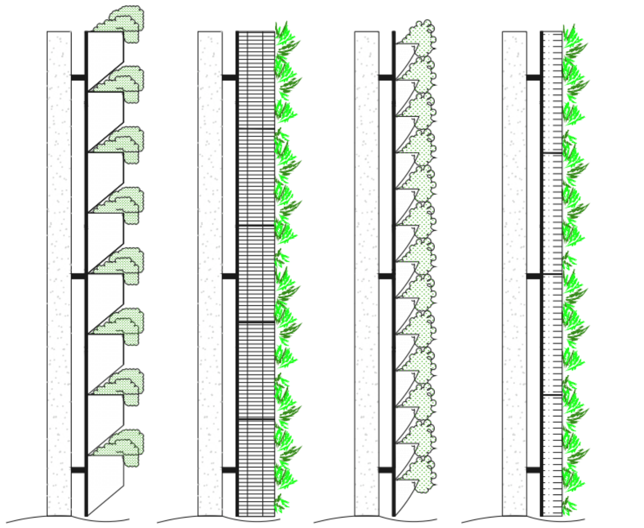


Figure 3.6 | Several Living Wall Systems, from the left to the right: Planter boxes, Foams, Laminar layers of felt sheets, Mineral woolpanels. | Source: (Ottelé, Haas, et al., 2011)

### 3.2.5 Maintenance

According to Ottelé, Haas, et al. (2011), the Living Wall Systems need to be maintained annually, with plantings pruned or replaced. The underlying irrigation system must be drained each year during the winter. When panels are used, a decision may also be made to replace a panel in its entirety.

### 3.2.6 Qualities

According to Liu et al. (2017):

- Improvement of building energy efficiency
- Health benefits
- Envelop protection
- Interior noise reduction
- Agricultural benefits
- Reduction Urban Heat Island Effect
- Positive psychological impact
- Providing biodiversity

### 3.2.7 Requirements

The plants are flammable when dry. Thus, a way must be found to prevent the plants from catching fire or the plants from being extinguished. If used in high-rise buildings, the irrigation system will also need to be a sprinkler system or fire baffles would need to be placed between the plants.

## 3.3 Bio-façade: Active Green Wall (AGW)

This is another form of green wall, as discussed in Section 3.2. In an Active Green Wall (AGW), unlike a Living Wall System, air flows not only through the *leaves* of the plants, but also through the *roots*. This provides better filter performance, but brings with it other requirements. An important difference with the LWS is that this system can in principle be placed entirely indoors. Nevertheless, in this study it serves as inspiration for a facade system, as presented in Section 7.3.

A capture mechanism that plays an important role in this filter technology, in addition to mechanisms such as intertial impaction and diffusion, is *direct interception*. When the air is passed through the roots on the substrate they will act as a kind of fibrous filter, a filter technology that is discussed in section 3.5.
The roots are the fibers in this process and cause particles to collide with them and remain behind. It is important that this root is not too dense to keep the pressure drop of the system low enough.

### 3.3.1 Application

Currently, a number of AGWs have been brought to market. One example is the AGW at the Lend Lease head office in Sydney as described in the research of Irga et al. (2017). In figure 3.7 a photo of this system is presented.

Figure 3.7 | Example of an existing Active Green Wall installation in the Lend Lease head office in Sydney. | Source: (Irga et al., 2017)

### 3.3.2 Filter quality

The filter quality indicates how well a filter performs at a certain pressure drop.

***Performance***

The study by Pettit et al. (2017) investigates how well an AGW system can filter particulate matter. This was investigated for eight different plant species and it is shown in figure 3.8 for five different categories of particulate matter, sorted by particle size.
For particles up to 2.5 µm an efficiency of up to 70% can be achieved and for particles up to 10 µm up to 90%.
This appears to be considerably higher than the filter performance of Bio-facade variant 1, as described in section 3.2.

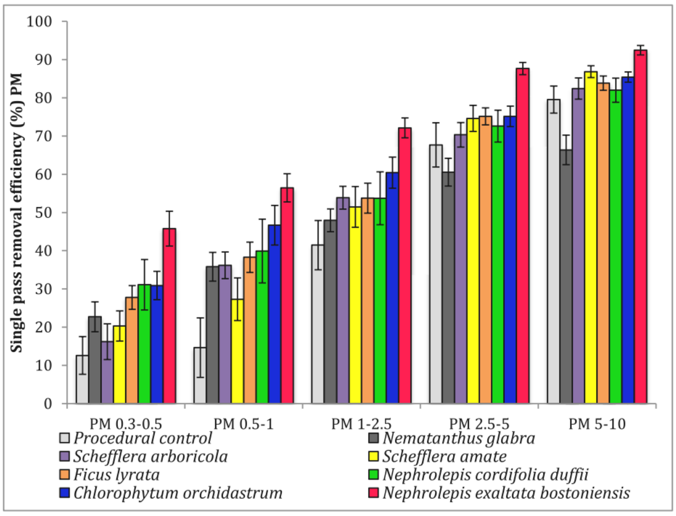



Figure 3.8 | For different plant species, the single pass removal efficiency was measured for five categories of particle size | Source: (Pettit et al., 2017)

***Pressure drop***

The root density determines to a large extent the pressure drop of the filter and, consequently, the filter performance. A plant species with a higher root density will capture more particulate matter because the capture mechanisms work better, but on the other hand the pressure drop will also increase. The question is therefore to what extent the filter quality increases with a certain plant species.
According to the research of Pettit et al. (2017), this pressure drop is around 20 Pa, which is also the limit value that the system must meet in this research.

The filter quality of this system is significantly better than that of the LWS when it comes to filtering particulate matter, as the performance is much higher.
When it comes to filtering $NO_2$, this system is comparable to the LWS.

### 3.3.3 Operating conditions

The operating conditions of this form of Bio-facade depend mainly on the plant species used in the system.

***Plant species***

In the case of the AGW, root density plays an important role in choosing the appropriate plant species. Each plant species has its own specific type of roots, as illustrated in figure 3.9.
The root density determines to a large extent the pressure drop of the filter and thus the filter performance.
A plant species with a higher root density will capture

more particulate matter because the capture mechanisms work better, but on the other hand the pressure drop will also increase. The question is therefore to what extent the filter quality increases with a certain plant species.

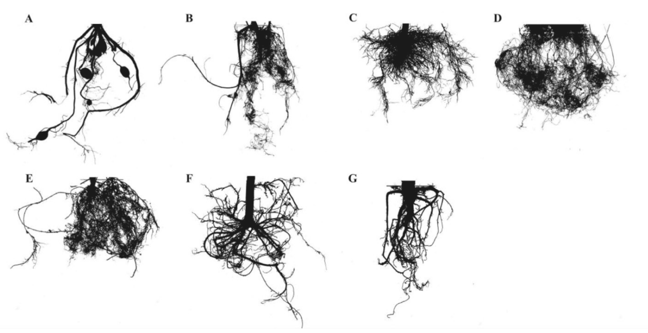



Figure 3.9 | Different root densities of several plants that can be used in an Active Living Wall | Source: (Pettit et al., 2017)

### 3.3.4 Construction and materials

An AGW can be designed for both indoor and outdoor use. The variant as discussed in the study by Pérez-Urrestarazu et al. (2016) is a panel consisting of a frame to which the substrate is attached and to which the plants are grown. Below the frame is a water pump that supplies the plants with sufficient water and nutrients through a pipe and through the substrate. A prototype of an ALW is described in the research of Pérez-Urrestarazu et al. (2016) and a schematic representation of it is given in Figure 3.10.

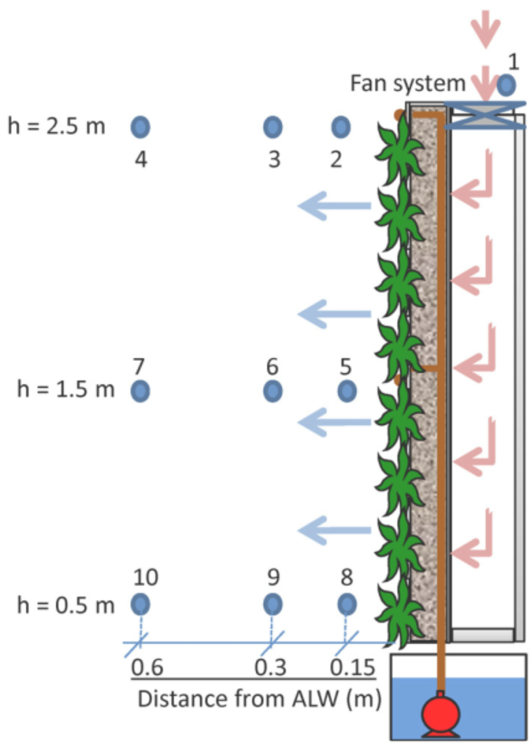



Figure 3.10 | Schematic figure of a prototype of an Active Green Wall | Source: (Pérez-Urrestarazu et al., 2016)

The frame of the AGW can be made of steel, while the substrate can be made out of different materials. In the example given by Pérez-Urrestarazu et al. (2016) a textile fabric is used which consists of polyamide and polypropylene.

***Substrate***

In the case of the AGW where the air flows through the roots and the substrate, the substrate should be as porous as possible to keep the pressure drop low. In this case, textile fabrics can be used. In the example of the AGW investigated in the study by Pérez-Urrestarazu et al. (2016), this substrate consists of a layer of polypropylene and polyamide interwoven into one textile fabric that the roots of the plants can adhere to and through which air can still flow well.

### 3.3.5 Maintenance

The maintenance of this system is similar to the maintenance of any other green facade. The advantage of this system is that the plants are more accessible and can be maintained from the inside. The maintenance effort with this technology is therefore much lower than with systems where the plants are on the outside.

## 3.4 Cyclone separator

A cyclone is a hollow and cone-shaped object through which air can flow. The shape causes the air inside to swirl and form what is known as a spiral vortex. The air spirals down the edges of the cyclone and is drawn back up the center towards the outlet.
This vortexing of the air is the mechanism behind the filtering of the particulate matter, as the particles fly out of their orbit due to the centrifugal force and collide with the side of the cyclone. Due to gravity, the particles then fall down towards the collection container. The principle of centrifugal force is a form of inertial impaction, as explained in section 2.2.4.
Figure 3.11 shows the cyclone and indicates how the airflow runs and where the particulates end up.

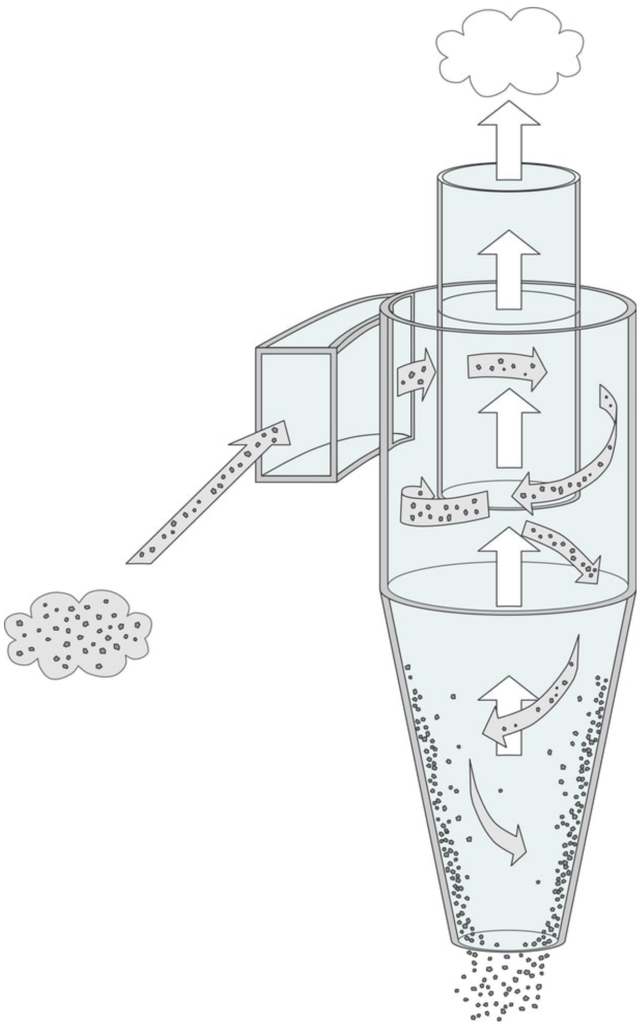


Figure 3.11 | Schematic figure of a cyclone separator. The small dots represent the particulate matter and the arrows the direction of the air flow | Source: (Solution Pharmacy, 2021)

### 3.4.1 Application

Cyclone separators are normally used for industrial applications where large amounts of dust need to be filtered. These cyclones are usually mechanically driven so that high air velocities can be achieved in the cyclones and thus high filter performance. Since the technology in this research does not have access to high wind speeds, the performance of the cyclones will not be as high as industrial, but research by Wolfson (2011) shows that even at low wind speeds the performance can still reach 70%.

An example of a design where cyclone separators are used is the so-called 'Breathe Brick', see figure 3.12. Here cyclones are built into large bricks with which a facade can be constructed by stacking the bricks. The airflow enters the cyclones through holes in the bricks and exits again in the cavity of the facade construction. Through further ventilation openings, the air can then be directed into the interior space.

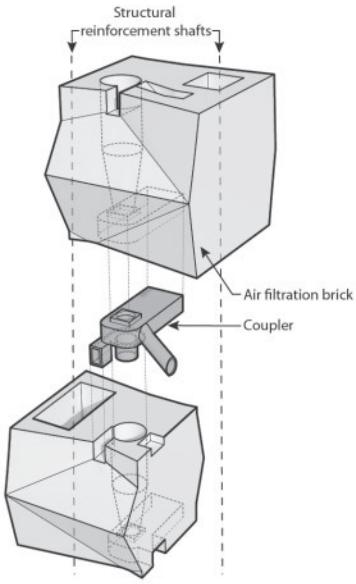



Figure 3.12 | Schematic figure of a so called 'Breathe Brick' construction. These are bricks that can be stacked, with cyclone separators integrated into the bricks. | (Trudell, 2015)

### 3.4.2 Filter quality

The filter quality indicates how well a filter performs at a certain pressure drop.

***Performance***

Wolfson (2011) writes in his book '*Energy, Environment and Climate'* that the efficiency of cyclone separators is between 50 and 99% when it comes to filtering particulate matter in a gas.
According to the research of Ji et al. (2009), a cyclone can achieve an efficiency of around 70% at an inlet velocity of 6 m/s. It should be noted that the air used for this purpose contains much higher concentrations of particulate matter than outside air. The performance will therefore be much lower in practice.
Research by Karagoz et al. (2013) achieves efficiencies of 80 to 94%, comparing two types of cyclones.
A note on these results is that these cyclones were tested with a mechanical air flow. Tests where cyclones are tested with a natural airflow are not known. It is expected that when a natural airflow is used the performance will be lower than the above values.

***Pressure drop***
Figure 3.13 shows the relationship of inlet velocity and pressure drop according to the study of W. B. Faulkner and B. W. Shaw (2006). At wind speeds around 7.5 m/s the pressure drop is 250 Pa. This is well above the maximum value of 20 Pa. However, this must be seen in relation to the shape of cyclone. When other openings or sizes of the cyclone are used the pressure drop can decrease.
The shape of the cyclone and the inlet velocity are the most important factors in causing the pressure drop in the cyclone.
For lower wind speeds no data was found, the expectation is that at lower wind speeds the pressure drop will also be low enough to still allow wind to pass through the cyclone. However, this will have to be investigated further in practice.
Also no results have been found of other types of cyclones that work with less pressure drop. This also needs further investigation.

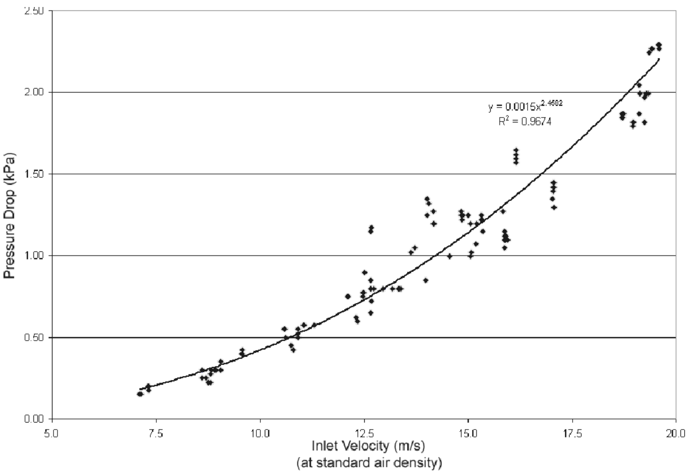



Figure 3.13 | Pressure drop as function of the inlet velocity of a cyclone separator | (W. B. Faulkner and B. W. Shaw, 2006)

### 3.4.3 Operating conditions
The filter quality of cyclone separators depends on several factors. The shape of the cyclone and the blow-in speed of the air are the most important factors and are therefore discussed below.

***Shape of the cyclone***
When the shape of the cyclone is adjusted to the characteristics of the air to be filtered, efficiency can be increased. In the research of W. B. Faulkner and B. W. Shaw (2006), the Texas A&M Cyclone Design (TCD) method is introduced for this purpose. This is a method that indicates for a type of cyclone what the ideal inlet velocity is to achieve the highest efficiency. In this way, the right cyclone can be chosen when the inlet velocity is known. It is imaginable that the TCD method could be used to design cyclones that operate at low wind speeds.
The shape of the cyclone affects the pressure drop, in further designing a cyclone this will be a limiting factor.

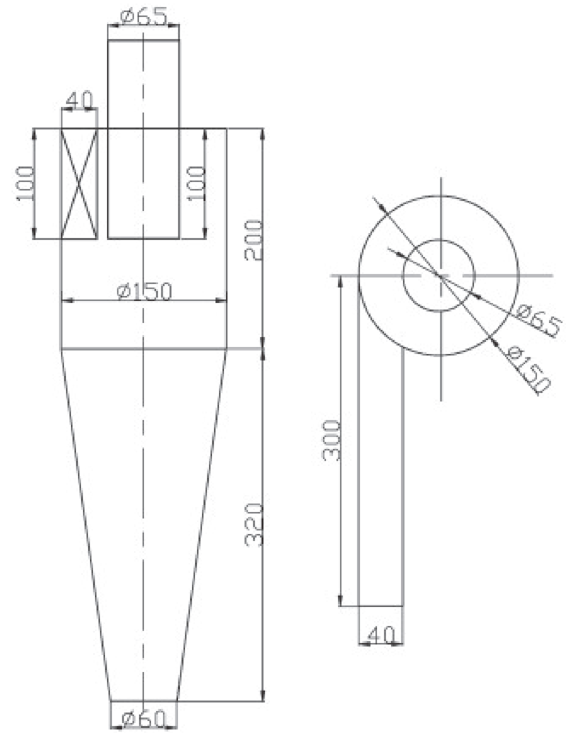



Figure 3.14 | Schematic representation of the cyclone. The dimensions of this cyclone are an example and are basically variable | (Ji et al., 2009)

***Inlet velocity***
The greater the speed at which the air enters the cyclone the better the filter works. This is mainly due to the fact that the centrifugal force on the particles becomes greater and therefore the particles fly out of orbit faster. This relationship follows from the studies of Ji et al. (2009) and Karagoz et al. (2013) and is shown in figure 3.14.

### 3.4.4 Maintenance
From time to time the cyclones must be cleaned in the following way:
- With water under high pressure
- Replacement of the lower part with the residue
- Replacement of the whole cyclone

If the lower part where the dust is collected is big enough the cyclone doesn't have to be cleaned during the lifespan, depending on the concentrations of the pollutants.
With ambient concentrations of particulate matter as is the case in this research this shouldn't be much of a concern. So it can be assumed that the maintenance frequency is very low during the lifespan of a cyclone.

### 3.4.5 Construction and materials
A cyclone is not very stable on its own due to its conical shape. Therefore, it is important to build a structure around the cyclone to contain it. Large cyclones are usually suspended in a steel structure.
In the Breathing Brick example, small cyclones are built

in stones. The bricks are then stacked and in this way a facade is created with all cyclones in it.

The cyclones can be made of different materials. Variants made of plastic seem the most obvious for this purpose, since the cyclones are built in.

### 3.4.6 Qualities

- When the collection trays in the cyclones are large enough, they do not need to be replaced or cleaned during the life cycle of the panel. This makes the system virtually maintenance free.
- The cyclones are reusable after being used in this panel and can be reused in another panel, pr vided that the material properties allow this.

### 3.4.7 Requirements

- Filters mainly large particulate matter. When used in a system, another technology will have to be applied to filter the smaller particles
- The cyclone must be carefully designed to keep the pressure drop low and increase efficiency at low wind speeds
- The openings of the cyclone must be carefully designed to prevent the wind from whistling and causing noise
- To keep the maintenance fequency low, the dus bin must be sized large enough

## 3.5 Fibrous filter: electret

A fibrous filter consists of a piece of fibrous material with a certain density, thickness and shape. The airflow is passed through this material, with the fibers of the filter taking care of filtering the particulate matter. When a particle collides with a fiber and the particle sticks to the fiber it is filtered out of the air. The main capture mechanisms here are direct interception and inertial impaction as described in section 2.3.

Fibrous filters mainly come in three variants: woven, non-woven and membrane. Non-woven and membrane filters dominate the market, with membrane filters usually being thick and applied in a mechanical system. When a fibrous filter is mentioned in this study it is almost always a non-woven filter.

***Electret filter***

An electret filter is a type of fibrous filter where the material of the fibers is a dielectric material, a material that has a quasi-permanent electric charge, as explained in section 2.2.3.

The appearance of the filter is almost the same, but the difference is mainly in the way an electret filter traps particulates. This involves attracting the particles to the fibers with electrostatic forces. These forces can act on both charged and uncharged particulate matter.

Because the electrostatic forces act at a much greater distance than the diameter of the particulate particles, the fibers of an electret filter can be further apart than in a normal fibrous filter. This means that with the same filter efficiency the pressure drop of an electret filter will always be lower.

Since a low pressure drop is a condition in this research, it is more logical to use electret filters. The emphasis of the explanation in this paragraph is therefore on the electret filter.

### 3.5.1 Application

The best known fibrous filter in the construction world is the HEPA filter, which is often placed in the air handling unit of a mechanical ventilation system. The high efficiency of this filter is mainly achieved by its high fiber density. As a result, the air can only be forced through the filter under high pressure. A typical pressure drop of a HEPA filter is around 3000 Pa, which is a factor of one thousand too much for the type of filter sought in this research. This chapter will look for ways to use the technique with lower pressure drop.

An example of a fibrous filter with a lower pressure drop is the G4 filter cloth, as shown in figure 5.15.

This cloth can be used in different ways and in different shapes and thicknesses.

Figure 3.15 | Photo of fibrous filter, which can be bought in the webshop 'WTW-filtershop' and is widely used in air handling units | Source: (wtw-filtershop, 2021)

## 3.5.2 Filter quality

The filter quality indicates how well a filter performs at a certain pressure drop.

Several types of fiber filters have been introduced to the market. The filters differ in shape, material and thickness, among other things. The fiber density is also an important property. All the properties of the different filters affect the performance and pressure drop of the filters. Figure 3.15 shows different types of fiber filters in order of efficiency.

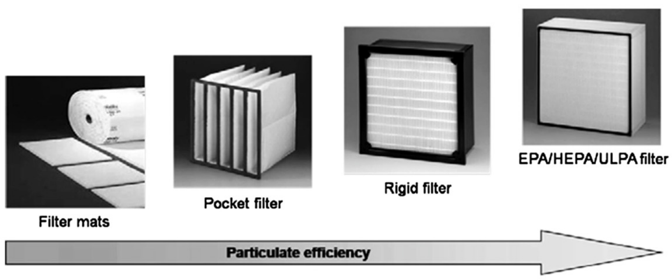



Figure 3.16 | Different types of fibrous filters and how they are related to the efficiency | Source: (Chavhan & Mukhopadhyay, 2015)

### *Performance and pressure drop*

The performance and pressure drops of different fibrous filters are tested in the research of van Turnhout et al. (1981). An electret filter with a density of 200 g/m$^2$ reaches a performance of 98% with a pressure drop of only 20 Pa. This is in contrast to a fibrous filter from a glass-fiber paper with a performance of 97.5%, but with a pressure drop of over 470 Pa.
The G4 filter cloth as shown in figure 3.16 has a pressure drop of 42 Pa at a thickness of 20 mm. The expectation is that with a thinner filter cloth the pressure drop will be below 20 Pa.
In general, the pressure drop increases with the efficiency of the filter. The pressure drop is therefore the limiting factor for the performance. Because this research is looking for options to keep the pressure drop low, the filters that can be used in this research will therefore not be the most efficient filters.

## 3.5.3. Operating conditions

Which parameters affect the performance of an electret filter is summarized in table 3.A. In this table it is shown whether a parameter has a positive or negative effect on the aerosol penetration, the filter quality or the most penetrating particle size.
The face velocity and charge density are the parameters that appear to have the most effect, especially on the filter quality.

| Parameters | Unit | Aerosol penetration | Filter quality | Most penetrating particle size |
|---|---|---|---|---|
| Face velocity | cm/s | ↑ | ↓↓↓ | ↑, ↓* |
| Fiber diameter | µm | ↑ | ↑ | ↑ |
| Packing density | — | ↓ | ↓ | ↓ |
| Filter thickness | mm | ↓ | — | ↓, —* |
| Charge density | C/m$^2$ | ↓ | ↑↑ | ↓ |

Table 3.A | Direction and magnitude of change in aerosol penetration, filter quality and MPS. | Source: (Huang et al., 2013)

### *Face velocity and retention time*

According to Huang et al. (2013), with a lower face velocity, especially more small particles ( < 1 µm) are filtered. The main capture mechanisms for these small particles are mainly electrostatic attraction and diffusion and these benefit from a lower face velocity and longer retention time.
It is therefore important to keep the face velocity on this filter low and to increase the retention time.

### *Charge density*

The charge density means the amount of charge per unit area of filter cloth and the higher this is the better the filter quality will be.
In an electret filter the particles are mainly attracted by the electrostatic forces. The more the fibers can cause of this the more particles will be attracted. It is therefore important to be able to charge the fibers as strongly as possible. How strongly a fiber is charged has no influence on the air resistance and therefore the most profit can be made with this.

### *Packing density*

The higher the packing density, the smaller the distance between the fibers. This means that the capture mechanisms *interception* and *impaction* work better and that the aerosol penetration and MPS will decrease.
The most important note here is that with increasing packing density the pressure drop of the filter also increases.
The filters that can be used with a pressure drop of up to 20 Pa are mainly the coarse filters with relatively low packing density.

***Geometry***
Also the geometry of the filter media plays an important role. A filter can be pleated or flat and can have a single layer or multiple layer behind each other. Different types are presented in image 3.16, which makes it clear that the geometry of the filter has influence on the performance of the filter.
The geometry also affects the pressure drop. The more the air is swirled through the geometry the more resistance it encounters and the bigger the pressure drop will be. The pressure drop of an equally thick pleated filter will therefore often be higher than that of an equally thick but flat filter. For this research filters cant be pleated too much, because the pressure drop must be kept low.

***Filter thickness***
According to Huang et al. (2013), making a filter thicker does not have the desired effect on the filter quality. This is because the electrically charged particles are mainly captured in the outer surface of the filter. Thus, a thicker filter is mainly useful for the non-charged particles, but at the same time it also causes a larger pressure drop.
According to Podgórski et al. (2006) the pressure drop of a fibrous filter is linearly dependent on the thickness of the filter. This can also be seen in table 3.A, where the quality factor remains the same with an increase in filter thickness.
The most important conclusion is that for a low pressure drop the filter should not be too thick.

***Fiber diameter***
The diameter of the fibers determines the amount of surface area. The smaller the diameter of the fibers the more contact the fibers have with the passing air. This allows more particles to be attracted and more space for particles to adhere. This is shown in the study by Huang et al. (2013) where the aerosol penetration decreases when the fiber diameter decreases.
However, the disadvantage is that filters with a similar fiber density, but a smaller fiber diameter, cause more pressure drop because between the fibers the air will swirl more and therefore be slowed down.
With decreasing fiber diameter, according to Huang et al. (2013), the effect of increasing pressure drop is stronger than decreasing aerosol penetration and therefore, with decreasing fiber diameter, the filter quality decreases.
Therefore, the filters used in this research should not have a fiber diameter that is too small, otherwise the pressure drop becomes too large.

***Fiber material***
The basic property of a material that can be used as electret is that the material is dielectric, for instance cotton and polymers. If the fibers are made from polymers which are water-repellent and thermally stable, the electrets are insensitive to moisture and high temperatures, according to van Turnhout et al. (1980)

### 3.5.4. Construction and materials
An electret filter consists mainly of filter cloth which is not rigid and stable on its own. It is therefore important that a sub-construction is used to hang or clamp the filter cloth.
For instance in the pocket filter and rigid filter, as shown in figure 3.16, the cloth is attached to a substructure to make the filter as whole a construction that can stand on its own.

***Moisture protection***
It should be prevented at all times that moisture can accumulate in the filter. This can cause mold and form a breeding ground for bacteria and viruses, which can be blown along with the air flow. The filter must therefore be placed in the facade in a way that rainwater cannot enter the filter and vapor from the building cannot condense in the filter as well.

### 3.5.5. Maintenance
Regular maintenance is required to clean the filters to prevent them from clogging up. When a filter becomes more and more clogged in the beginning, the aerosol penetration will decrease. The dirt forms a kind of cake on the outside of the filter, reducing the distance between the fibers. However, when the filter becomes more saturated, the pressure drop of the filter also increases and the filter quality decreases. Eventually the filter can become so clogged that the air cannot flow through it anymore.
Cleaning the filters is not easy to do on site. It is therefore wiser to replace the filter cloth on site and possibly clean it at the factory for reuse.

### 3.5.6 Qualities
- The filter doesn't require a supply of electric power. The fibers are permanently charged and the incoming particles don't have to be pre charged either.
- Fiber filters are by definition very light.
- Fiber filters are often made of cloth and can therefore be designed in all desired sizes and shapes.
- Fiber filters are relatively easy to install in existing facades and ventilation systems and therefore suitable for renovation projects.

### 3.5.7 Requirements
- A fiber filter should be cleaned or replaced at least annually in normal use. The filter must therefore be easily accessible in the construction

of the building.
- The filter must be protected from rainwater and vapor at all times.

## 3.6 Analysis

### 3.7.1 Summary
Table 3.C on the next page summarizes the performance, pressure drop and maintenance frequency of the various technologies, as described in previous sections.

### 3.7.2 Criteria
In order to compare the different air purification technologies, criteria have been formulated for the following three properties: the filter quality and the maintenance frequency.
These criteria are shown in table 3.B. A technology can be given a score from 1 to 3 for each property, whereby the higher the score the better.

| Filter quality $NO_2$ | Filter quality PM | Maintenance frequency |
|---|---|---|
| 1. Performance: << 50%<br>2. Performance: around 50%<br>3. Performance: >> 50% | 1. Classification: ISO ePM10 / coarse Pressure drop: > 20 Pa<br>2. Classification: ISO ePM2,5 Pressure drop: around 20 Pa<br>3. Classification: ISO ePM1 Pressure drop: < 20 Pa | 1. Multiple times a year<br>2. No more than once a year<br>3. No maintenance during lifespan only accidentally |

Table 3.B | The three criteria that form the basis to compare the different technologies with each other. For every criteria three scores are defined | Source: own work

The *filter quality* says something about the performance of a filter in relation to the pressure drop that is required for this as is explained more in detail in paragraph 6.3.

The lower the *maintenance frequency* the better, since high buildings are often difficult to reach for maintenance personnel

| Technology | Performance $NO_2$ [%] | Performance PM [%] | Pressure drop [Pa] | Maintenance frequency |
|---|---|---|---|---|
| **PCO with $T_iO_2$** | Differs per application:<br>Mineral silicate paint: 27%<br>Styrene acrylic paint 71%.<br><br>For this study, the value is estimated to be in between: (50%) | - | - | Should be washed once every two months. This can be done with rainwater. Coating should be replaced after several years, depending on the processing and material. |
| **Bio-facade: Living Wall System** | 25% | 14-20% | Low | More than once per year |
| **Bio-facade: Active Green Wall** | 25% | PM2.5: up to 70%<br>PM10: up to 90% | Between 20-30, depends on root structure | More than once per year |
| **Cyclone separator** | - | Between 50 and 90%. At low wind speeds and high concentrations of particulates around 70%.<br>Filters only coarse particles. | At inlet velocity of 7.5 m/s around 250 Pa in this example. With a different shape cyclone a lower pressure drop can be achieved. | No information was found on how quickly the collection trays become full. The assumption is that at low concentrations of particulate matter in the air during the lifetime of a façade panel this will not be necessary. |
| **Fibrous filter** | | 98% (Not known what particle sizes) | 20 | Must be replaced at least 1x per year. |

Table 3.C | Summary of the most important properties of the different technologies. | Source: own work

# Conclusion

- ***How can the different technologies be com pared to each other?***

In this Chapter the different air purification technologies were discussed. To answer this research question, they were evaluated according to three criteria, the *filter quality of $NO_2$ and PM* and the *maintenance frequency.* In table 3.D in paragraph 3.7.2 these criteria are presented.

***Result***
The result of this analysis is given in table 3.D. These values serve as a guideline for evaluating the concepts in chapter 7.

| Technology | Filter quality $NO_2$ | Filter quality PM | Maintenance frequency |
|---|---|---|---|
| PCO with $T_iO_2$ | 2 | - | 3 |
| Living Wall System | 1 | 1 | 1 |
| Active Green Wall | 2 | 2 | 1 |
| Cyclone separator | - | 1 | 3 |
| Electret filter | - | 2 | 2 |

Table 3.D | The result of the analysis of the different air purification technologies | Source: own work

Only one of the technologies filters significant amounts of $NO_2$ in an efficient way, the technique PCO with $TiO_2$. The bio-facade also theoretically filters $NO_2$, but these do not represent significant amounts. Therefore it seems obvious to use PCO as the leading technology for filtering $NO_2$ in this research.

For the filtering of particulate matter, several technologies have been looked into. In contrast, none of these technologies can achieve a high filter quality, score 3, without also requiring a high pressure drop.
When the smallest particles have to be filtered it is inevitable that the pressure drop will increase.

How much maintenance these technologies need is strongly dependent on the dust holding capacity. Only in the case of a cyclone does it seem possible to make a container for the particulates that is large enough that it does not need to be emptied during the whole lifespan. With the technology PCO with $TiO_2$ it is important that the surface remains clean, so that the catalyst can remain in contact with the polluted air, which is usually done automatically by the rain. In general, this technology does not need maintenance during the lifespan.

# 4

# State of Art: Building ventilation

In this chapter the basic information and the State of Art of the building ventilation is presented.

The main purpose of ventilation is to provide fresh air to the people in the building. This should be done in a correct way to prevent people from suffering from the so-called Sick Building Syndrome, as described in Biler et al. (2018).
Draughts, humidity, temperature and noise must be taken into account when designing ventilation openings. Regulations are available for this purpose through the Dutch Building Code.

The paragraphs and sub research questions are as follows:

- ***4.1 Ventilation conditions***

Ventilating in a natural way in the facade can be done in different ways and under different conditions. The main factors that influence the quality of ventilation are outlined in this paragraph.
The research question in this paragraoh is:

- ***Which conditions must be taken into account when designing ventilation openings?***

- ***4.2 Ventilation openings***

The openings in the facade through which air can flow are the basis for natural ventilation. The main types found in the building industry are outlined in this section.
The research question in this section is:

- ***Which ventilation openings are relevant for this research?***

- ***4.3 Analysis***

The different ventilation openings are evaluated according to three criteria and are compared to each other.
The research question here is:

- ***How do the different ventilation openings relate to each other?***

# 4.1 Ventilation conditions

Ventilating in a natural way in the facade can be done in different ways and under different conditions. The main factors that influence the quality of ventilation are outlined in this paragraph.

## 4.1.1. Facade construction

Two types of facade construction are important to consider when thinking of natural ventilation trough the facade: the double facade and the cold facade.

***Double skin facade***

When air is brought into a high-rise building in a natural way, it is most often done through a double skin façade construction, according to the research of Etheridge and Ford (2008).

This is a construction in which the facade consists of two parts: an insulated inner layer and an uninsulated outer layer. Between these two parts there is then a layer of air that serves as a buffer between the inside and outside. The ventilation air is first introduced into the cavity, where it mixes with the already warmer air before passing through the insulated inner layer into the room. See Figure 4.1 for a schematic illustration of this.

In this cavity, the airflow can be slowed down, reducing the chance of drafts. Also, the air can be additionally preheated here using sunlight and heating elements or cooled with Phase Change Materials. The acoustic value will also improve due to the air layer in the cavity.

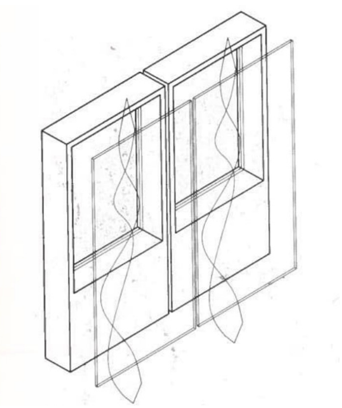


Figure 4.1 | Schematic illustration of a 'Second-skin' facade | Source: (Knaack et al., 2007)

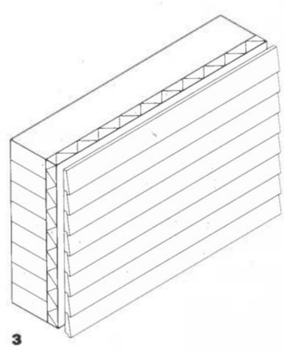
***Cold facade***

A so-called 'cold facade', in which the outer facade layer is separated from the insulation layer by a cavity , also provides a buffer between inside and outside.

Figure 4.2 shows a schematic example of such a facade type.

Here, the ventilation air could first be led into the cavity, after which it enters the room through another opening through the insulation layer.

The main benefits of a cavity are moisture control, soundproofing and thermal insulation.



3

Figure 4.2 | Schematic illustration of a 'Cold' facade | Source: (Knaack et al., 2007)

***Direct or indirect air flow***

The construction affects how the air flows through the facade. This can be a *direct* air flow, where the air flows directly through the vent from outside to inside.

It can also be an *indirect* air flow, where the air is first introduced into a buffer zone, such as in a double facade or in a cavity. The indirect air flow usually has advantages over the direct air flow when it comes to air circulation, thermal comfort and acoustics.

## 4.1.2. Position in facade.

The location of the ventilation opening mainly affects the air circulation of the incoming air with the air that is already in the room. For a cold climate like the one in this study, a high position makes more sense than a ventilation opening near the ground.

***High position***

A ventilation opening at a higher position in the façade is desirable in colder climates, because the cold air wants to flow downwards, thus creating air circulation with the warmer air in the room that wants to flow upwards. In doing so, however, proper heating must be provided in order to have a warm air flow that is strong enough to prevent cold draughts.

In warmer climates, a vent at a high position makes less sense because the warm air will enter the room at the top where there is already warm air. This will create less air circulation.

***Low position***

Air can also be introduced at a low position, as shown in Figure 4.3.

This option is mainly desirable in warmer climates, because the warm air entering will rise and thus cause air circulation with the colder air in the interior space low to the ground.

For cold climates, this solution is less desirable, because the cold air entering will remain suspended just above the floor, where it will not come into contact with warm air and will not heat up quickly.

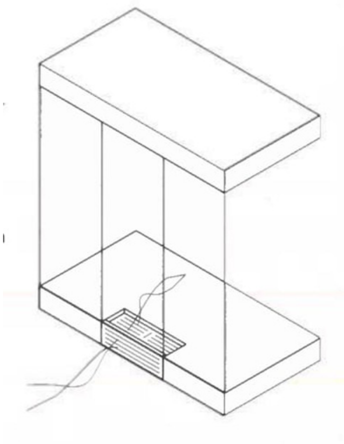


Figure 4.3 | Schematic illustration of a facade where the air enters the room through a ventilation opening low to the floor | Source: (Knaack et al., 2007)

### 4.1.3. Type of opening

Which openings are used in a facade largely determine the pressure drop and noise propagation of the system, according to Christoforidou et al. (2019). Also, the shape, size and location of the openings in the façade largely determine how the air enters the room, how well the air mixes with the indoor air and whether there are drafts and inconvenient temperature differences.
In this study, a distinction is made as to whether the air enters the interior space directly or indirectly. It also distinguishes whether the air enters the room in a concentrated or distributed way.

***Concentrated or distributed air flow***

When a ventilation opening is located at one concentrated place in the façade, this is called a concentrated air flow. Examples are ventilation openings such as a window and a wall ventilation opening.
If a ventilation opening consists of several tiny openings, distributed across the facade, this research refers to a distributed air flow. The air enters the room at several locations at the same time.\

***Pressure drop***

In general, if the pressure drop of the ventilation openings is higher, for example 10 Pa instead of 1 Pa, the pressure differences of the wind falling on the façade can be better absorbed and are less noticeable in the room. On the other hand, the pressure drop of the opening should not be too high, otherwise the wind will not enter the building at all.
For the design of a ventilation opening a pressure drop that is not too low and not too high is desirable. The boundary condition regarding the pressure drop has been calculated for this study at 20 Pa as the maximum pressure drop.

## 4.2 Ventilation openings

The openings in the facade through which air can flow are the basis for natural ventilation. The main types found in the building industry are outlined in this section.

### 4.2.1. Operable window

The most common way of natural ventilation is a window that can be opened. Different ways in which a window can be opened are shown in Figure 4.4. The qualities of a window are mainly that the occupant has a lot of influence on how wide the opening can be set.
When a window is opened a direct connection is created between inside and outside, without heat recovery, pressure drop or protection from precipitation and noise. Opening a window also quickly create air drafts. This makes an operable window unusable in harsh weather conditions. To be able to use an operable window in a high-rise, it is often used in combination with a double skin façade construction.

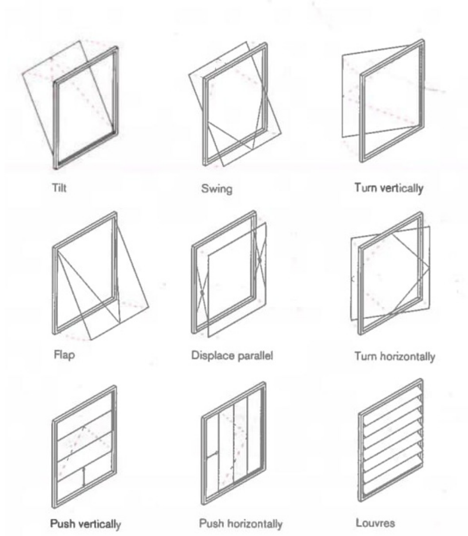



Figure 4.4 | Schematic illustration of an operable window and in what ways it can be opened | Source: (Knaack et al., 2007)

***Night ventilation window***

This is a type of operable window where a ventilation grid covers the hole when the window is open. Usually a tilt window is used as shown in figure 4.5. In this way the room can be ventilated, while the interior space is protected.

Figure 4.5 | Schematic illustration of an operable window and in what ways it can be opened | Source: (Knaack et al., 2007)

4.2.2. Operable vent

Many types of operable vents are conceivable for ventilating a space. Factors on which to select range from how sound-absorbing and fire-resistant they are, whether there is pre-heating and how suitable they are for use at great heights or in a renovation project. Also the size, flow rate and how they connect to what type of window frame plays an important role.
It is possible to install an operable vent in an existing window frame, but the glass must be replaced. Trickle vent This is a type of operable vent consisting of a very narrow opening, which can be opened and closed with a push-button.
It is possible to install an operable vent in an existing window frame, but the glass must be replaced.

***Trickle vent***

This is a type of ventilation grille that consists of a very narrow slit. Its main purpose is to get as little ventilation in as possible and avoid any problems caused by large wind pressure differences on the façade.
According to Biler et al. (2018), when used in high-rise buildings, it is a favorite alternative to operable vents. Trickle vents can come in several varieties, as illustrated in Figure 4.6.

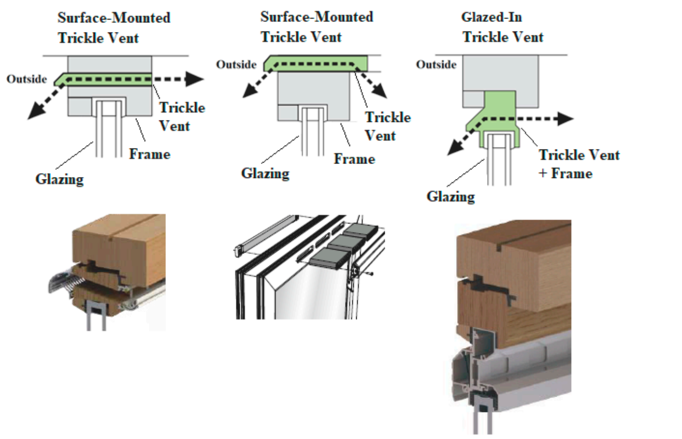



Figure 4.6 | Examples of 'trickle vents' | Source: (Biler et al., 2018)

### 4.2.3. Ventilation grille

Ventilation grilles are available in different variations and can be placed in a hole in different sizes. The louvers of the grilles are designed to prevent rain penetration. The precise shape of the louvers can be designed as desired, for example, it is also possible to incorporate acoustically absorbent material into them, as shown in Figure 4.7.

Figure 4.7 | A ventilation grille with acoustic absorbing material integrated, from manufacturer Duco under the name 'Duco Acoustic Panel 150'. | Source: (DUCO, 2021)

### 4.2.4. Wall ventilation opening

A wall ventilation opening is usually applied to already existing walls, where afterwards the ventilation needs to be added.
The advantage here is that it is a relatively small operation to create a ventilation opening. The existing construction needs only little adjustment.
The disadvantage of wall ventilation is that the air flows from a concentrated hole into the interior space. This does not promote air circulation and can cause draughts. In the example that is presented in figure 4.8 heavy sound attenuation has been applied. This solution is ideally suited for situations with heavy noise exposure on the facade.
The thermal properties on the other hand are very poor, the RC value of this system is 0.21 $m^2$*K/W.

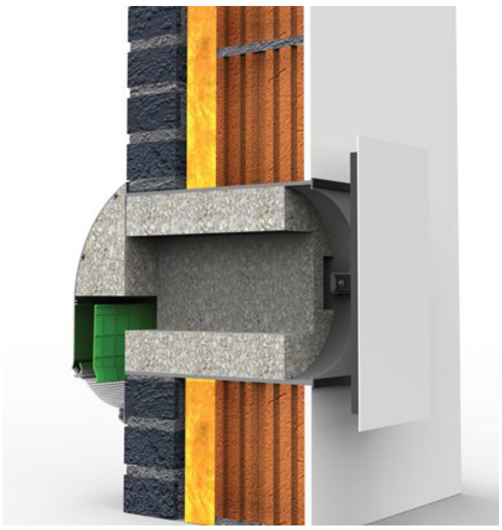


Figure 4.8 | Render of a Wall ventilation opening | Source: (DUCO, 2021)

### 4.2.5. Mashrabiya

This is a type of opening that is common in the Middle East. It usually consists of a form of masonry through

which, often in an ornamental manner, openings have been made for air to flow through freely. Figure 4.9 shows a photograph that is an example of a Mashrabiya. The fact that this is often used in warmer climates is mainly due to the fact that it is just a hole without any kind of other function except an aesthetic one and an air passage. The air circulation cannot be regulated, the air cannot be cooled or preheated, nor are acoustic attenuation measures applied.
Therefore, when applying such a vent in a colder climate, it will always have to be applied in combination with an air cavity.

Figure 4.9 | Photograph of an example of a 'Mashrabiya' applied in a high-rise building | Source: (designboom, 2012)

## 4.3 Analysis

### 4.3.1 Criteria

To answer the research question, the six ventilation openings were analyzed on the following three criteria: air circulation, thermal comfort and acoustics. These criteria and how the scores 1 to 3 are structured is shown in table 4.A. A high score means that the ventilation opening scores well on the corresponding criterion.

The result of the analysis is presented in the conclusion of this chapter.

| Air circulation | Thermal comfort | Acoustics |
|---|---|---|
| 1. Location: wrong regarding climate conditions<br>Opening type: too big or too low pressure drop<br>2. Location is good but opening type is not good or the other way around<br>3. Location: right spot regarding climate conditions<br>Opening type: smaller openings with enough pressure drop to prevent draft | 1. No measures taken to cool or heat air<br>2. Can only cool or only heat air<br>3. Can both cool and heat air | 1. No possibilities for improving sound attenuation / Risk that air flow in system causes noise<br>2. Some possibilities for improving sound attenuation<br>3. A lot of possibilities for improving sound attenuation |

Table 4.A | The three criteria that form the basis to compare the different ventilation openings with each other. For every criteria three scores are defined | Source: own work

For the air circulation the location where the air enters the room and whether the type of opening can cause a draft were considered. For thermal comfort it was considered whether the ventilation opening offers possibilities for cooling or preheating the air and for the acoustical properties whether the ventilation opening offers possibilities for acoustical attenuation. These criteria are further explained in section 6.3.

# Conclusion

- ***Which conditions must be taken into account when designing ventilation openings?***

Two factors are important when designing ventilation openings: proper air circulation and preventing drafts. When air does not circulate properly, there can be local temperature differences in a room, due to cold downdrafts, for example. With drafts, the wind speed is too high locally, which can cause a colder wind chill or other discomfort.

To create good air circulation in a room and prevent drafts, three conditions must be observed.
First, the *facade construction* is important. Systems such as a double skin facade or a cold facade reduce the chance of drafts because the air in the cavity is slowed down. The construction influences whether the air enters the facade directly or indirectly through a buffer zone.
Secondly, the *position* of the ventilation openings in the façade is important. In cold climates, a high position in the façade is better for air circulation, because the cold air then mixes with the rising warm air in the room.
The third condition is the *type of opening* applied in the façade. Here the geometry of the opening makes a difference to the air flow rate and the chance of local drafts. The pressure drop of the opening also plays a role, the larger the pressure drop the better the pressure differences on the facade can be absorbed. A ventilation opening can provide a *concentrated* or a *distributed* airflow, whereby the latter is preferred when it comes to evenly distributing the air in the room.

- ***Which ventilation openings are relevant for this research?***

In this study, existing ventilation openings were examined, outlined and compared. These include the following five: *operable window, operable vent, ventilation grille, wall ventilation* and the *mashrabiya.*

- ***How do the different ventilation openings relate to each other?***

To compare the ventilation openings they are evaluated according to three criteria: *air circulation, thermal comfort* and *acoustical properties.* The criteria are presented in table 4.A in paragraph 4.3.1 of this chapter.

In table 4.B the result of the analysis is shown. These values serve as a guideline for evaluating the concepts in Chapter 7.

| | Air circulation | Thermal comfort | Acoustics |
|---|---|---|---|
| **Operable window** | 1 | 1 | 1 |
| **Double facade** | 2 | 2 | 3 |
| **Operable vent** | 3 | 3 | 3 |
| **Ventilation grille** | 1 | 1 | 3 |
| **Wall ventilation** | 1 | 1 | 3 |
| **Mashrabiya** | 1 | 1 | 1 |

Table 4.B | The result of the analysis of the different air ventilation openings | Source: own work

From this analysis it can be concluded that the operable vent by itself is the best choice in terms of air circulation, especially in cold climates where this type is placed at the top of window frames. A double facade is also a good option in this case, as the cavity provides a buffer.
In terms of thermal comfort, the double facade and the operable vent are the best choices. The air in the cavity can be preheated by sunlight in summer and in an operable vent insulation material can be placed.
The acoustical sound attenuating measures can be well integrated in no less than four ventilation openings. In a ventilation grille, for example, this can be applied in the louvers.

This analysis shows that the operable vent and double facade generally score well and are therefore almost always a good choice. The Mashrabiya and operable window, on the other hand, are not good choices on their own. If one chooses one of these types, adjustments will have to be made to the design of the ventilation opening or the construction supporting it.

# 5
# Validation: Testing several filters

Testing with the self-made test setup was done with two main goals. The first is to investigate whether reliable testing is possible with such a home test setup and which challenges are encountered.
The second goal is to test existing filters and new materials at wind speeds and a pressure build-up similar to outdoors and use the results to make design choices.

The two research questions of this chapter are as follows:

- ***Is it possible to test filters at home for their per formance and pressure drop?***
- ***How can the test results support the design?***

- ***5.1 Test set-up***

This section describes how the test set-up was made and the equipment needed for it.

- ***5.2 Test protocol***

This paragraph explains the method by which the tests were performed.

- ***5.3 Test results***

The results of the tests are presented in this section.

- ***5.5 Interpretation of the results***

The reliability of the results is described in this paragraph.

## 5.1 Test set-up

This section describes how the test set-up was made and the equipment needed for it.

### 5.1.1 Complete set-up.

The test setup consists mainly of an airtight cardboard box with plexiglass on one side so that the inside is visible. On the left side a computer fan is placed in the box, the speed of which can be controlled by a lab power supply. The fan can blow wind through the box and a cutout has been made in the bottom to be able to add smoke to the airflow, see figure 5.1 for a close-up of this.
At at a distance of three-fourths of the tube the test object is placed. Both at the front and at the back the amount of particulate matter and the wind speed were measured with a PM meter and a wind speed meter. The PM meter is connected to the computer so that the results can be read and stored immediately. See figure 5.2 for a overview of the complete test-set-up.

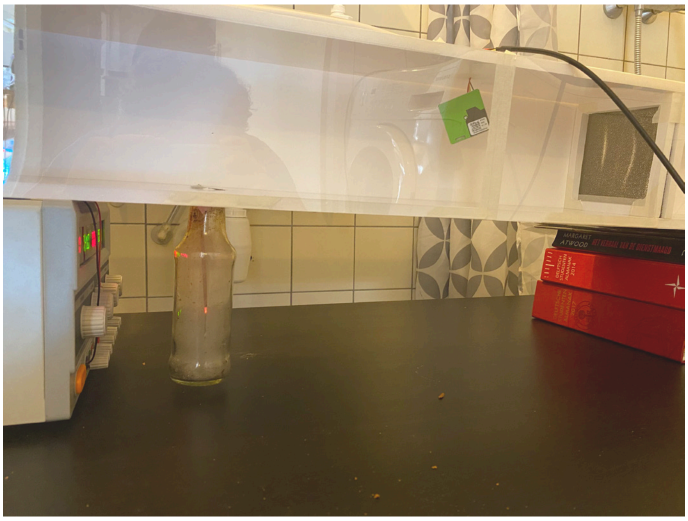


Figure 5.1 | Close-up photo of the lab power supply, the fan, and the incense as a source of smoke | Source: own work

Figure 5.2 | Photo of the complete set-up | Source: own work

The difference in air quality of the air before and after the filter was used to say something about the performance of the filter. See figure 5.3 to see how the PM meter was placed in the tube to make measurements. The difference of the wind speed in an empty tube and in a tube with a filter was used to estimate the pressure drop of the filter.


Figure 5.3 | Close-up photo of the test object and the PM meter placed before it | Source: own work

The design of this test set-up is based on tests found in the literature review. Figure 5.4 shows a schematic representation of a test as performed in the study by Hyun et al. (2016).
The difference is that the test of Hyun et al. (2016) was performed under laboratory conditions and with a mechanical air flow, where more pressure and wind speed can be produced.

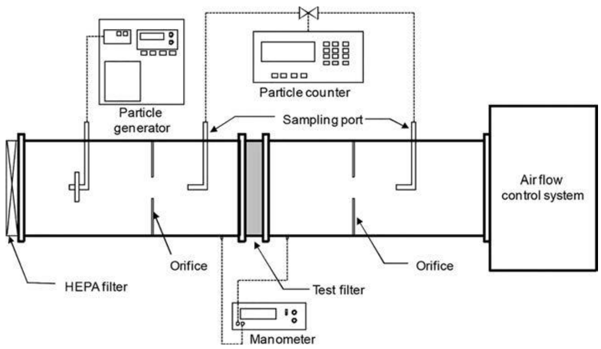



Figure 5.4 | Schematic drawing of a test set-up found in literature | (Hyun et al., 2016)

### 5.1.1 Components of the set-up

***Computer fan***

The following computer fan was used as the fan: 'Sunon EEC0381B1-000U-A99 V/DC', see figure 5.5. It is connected to a standard lab power supply. Via the lab power supply it is controlled how much voltage the fan will be given and therefore how fast the fan will run. The maximum amount of voltage this fan can handle is 12V. In this experiment three modes were used for the fan: 4V, 7V and 12V. In an empty tube, these modes cause wind speeds as shown in table 5.A. At the lowest setting, the fan causes an average wind speed of 1.6 m/s in the tube and at the highest setting it is 4.6 m/s.

This computer fan had the most airflow per $m^3$ which can be used at low Voltage and the air speeds it cause approach the actual wind speeds that act on a facade.

| | 1 | 1A | 2 | 3 | 4 | 5 | Avg. |
|---|---|---|---|---|---|---|---|
| 4W | 1.4 | 1.6 | 1.7 | 1.7 | 1.7 | 1.7 | 1.6 |
| 7W | 2.6 | 3.1 | 3.3 | 3.3 | 3.3 | 3.3 | 3.2 |
| 12W | 4.0 | 4.4 | 4.6 | 4.8 | 4.9 | 4.9 | 4.6 |

Table 5.A | The wind speeds caused in an empty tube when the fan is given different amounts of voltage | Source: own work


Figure 5.5 | Photo of the computer fan 'Sunon EEC0381B1-000U-A99 V/DC' that is used in the test set-up | Source: (Webshop: Conrad, Manufacturer: Sunon)

***PM meter***

To measure particulate matter, the PM meter 'Sensirion SPS-30' was used, see figure 5.6 for a photo. The amount of particulate matter is displayed in µm/m3 for the following four different particle sizes: PM1.0, PM2.5, PM4.0 and PM10. According to the manufacturer, the range of the amount of particulate matter in the air that can be measured is between 1 and 1000 µm/m3 . Here, the accuracy of the device up to 100 µm/m3 is about 10 µm/m3 and from 100 to 1000 µm/m3 is about 10%.
The meter can be connected to the computer and immediately displays the results. The results can be read immediately and saved after the measurement is completed.

According to a researcher, Lattanzio (n.d.), who works for the manufacturer, the sensitivity of the PM meter is:
- 0.3 < 1
- 1 < 2.5
- 2.5 < 4
- 4 < 10

Figure 5.6 | Photo of the PM meter 'Sensirion SPS-30' that is used in the test set-up | Source: (Manufacturer: Sensirion)

The PM meter has an inlet and outlet. By using a small fan in the PM meter, air is led from the inlet through the device to the outlet. When measuring, it is important that the air flow coming from the outlet remains separate from the air flow going into the device. This is to prevent recirculation of contaminated air. As an extra measure to prevent this from happening, a frame was built around the PM meter using cardboard, as shown in photo 5.7.

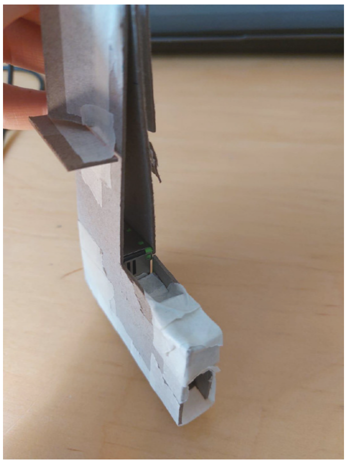


Figure 5.7 | Photo of the PM meter with a cardboard casing, to seperate the air flows, that is used in the test set-up | Source: own work

***Anemometer***

An anemometer with an accuracy of 0.1 m/s was used to measure wind speed. This meter is placed through a hole in the top of the tube in such a way that the propeller is placed in the middle of the tube and measures the laminar airflow. See figure 5.8 for a photo of the anemometer.

Figure 5.8 | Photo of the anemometer that is used in the test set-up | Source: own work

*Pollution source: incense*

In reference studies, several examples come up such as salt granules, cigarette smoke, and incense. For this study, incense was chosen for practical reasons. Also, incense has a relatively uniform distribution of particulate matter in different sizes.

## 5.2 Test protocol

This paragraph explains the method by which the tests were performed. Different actions are presented and in the end also a set-by-step plan

### 5.2.1. Burning incense

The first step is to stick a piece of tape to the incense stick, so that the stick can be hung in the bottle.
After the piece of tape is stuck to the stick, the second step is to light the stick.
As a final step, the burning stick can be attached upside down in the bottle.
Now the bottle of burning incense is ready to be placed under the tube.

### 5.2.2. PM meter installation

At wind speeds greater than 1 m/s, the PM meter should be placed with the openings on the side that is not facing the wind.
To prevent recirculation of polluted air into the PM meter it is important that the PM meter is placed in the laminar airflow.
The air flow created by the fan starts in the tube as a turbulent flow. Only after a certain distance the air flow becomes laminar.
When the air flow then passes through the filter, vortices also occur just before and just after the filter. The measuring equipment should therefore be placed with sufficient distance from the fan and the filter.

### 5.2.3. Taking Measurements

For each test, two separate measurements are taken, which together form a total measurement.

*Single measurement*

Each measurement is made by measuring approximately 2 minutes before the filter and 2 minutes after the filter. This is done while using the same incense stick as smoke source and the same wind speed. When a different wind speed is used or a different filter is placed, a new incense stick is placed and a new single measurement starts.

*Total measurement*

Each filter is measured in total at three wind speeds, generated by driving the fan at a certain voltage, as explained in paragraph 5.1.1. A total measurement of a filter is finished when for each of the three wind speeds a separate measurement has been made. Thus, for each total measurement, three separate measurements are made.

### 5.2.4 Set-by-step plan

1. Insert the appropriate test object into the tube.
2. Connect the fan to the lab power supply
3. Make sure all openings in the box are closed except the inlet and outlet
4. Apply the desired voltage to the fan
5. Measure the wind speeds at locations 3 and 5 and record them
6. Place the PM meter at location 3
7. Start the PM measurement
8. Light the incense and place it in the bottle under the opening
9. Set the timer to 2 minutes
10. Check that the measurement is going correctly
11. Remove the PM meter from the location before the filter after 2 minutes.
12. Place the PM meter at the location after the filter and start the next measurement.
13. Stop the measurement after another 2 minutes.
14. After the measurement, remove the incense and blow clean air through the tube.
15. Analyze the results

### 5.2.5 Checks during testing

- The incense stick must be properly seated and burning in the bottle
- The fan must be set to the right speed
- The PM meter must hang in the middle of the tube with the openings on the leeward side
- Between measurements, the tube should be blown clean with the fan and without incense

### 5.2.3. Deriving values from the graphs

The results are read by drawing a line, which is an estimate of the average of the results. See figure 5.9 for an example of a measurement where these lines are drawn. Two peaks are visible in each measurement. The first peak represents the measurement before the filter and the second peak represents the measurement after the filter.

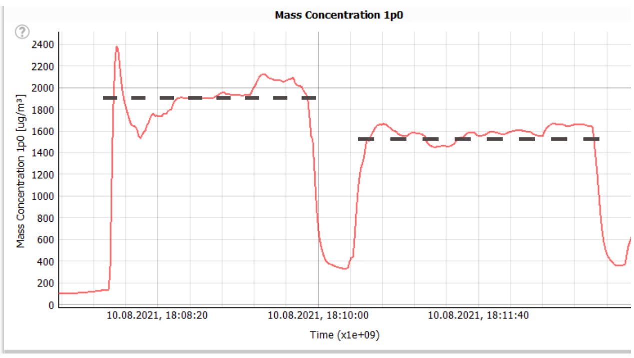



Figure 5.9 | Example of a measurement result with the averages of the peak before the filter and the peak after the filter indicated as black dotted lines | Source: own work

## 5.3 Test results

The two values measured in the test are the *performance* and *pressure drop* of a filer. This is measured at different wind speeds. With this the measurement can also say something about the effect of the wind speed on the performance.
The raw data of the measurements can be found in Appendix I.

***Test objects***
Two tests have been conducted. The filters that are tested are a 'ventilation grill filter' and a 'G4-filter', see figures 5.11 and 5.13. These are standard filters, ordered via wtw-filtershop (2021).

### 5.3.1. Converting data into pressure drop and performance

From the raw data the values were obtained for three different particle sizes and for three different wind speeds. These values were then used to determine the pressure drop and performance with the formulas described below.

***Pressure drop***
The pressure drop of the filters is calculated with the dynamic pressure formula:

$$P_w = \frac{\rho * \Delta v^2}{2}$$

with:
ρ = air density, for this case 1.25 [kg/ m$^3$]
$\Delta v = v_{empty} - v_{filter}$

***Performance***
To determine the performance of the filters, the percentage difference of the concentration of particulate matter in the air before the filter and after the filter is calculated according to the following formula:

$$Performance = \frac{Concentration_{before} - Concentration_{after}}{Concentration_{before}} * 100\%$$

### 5.3.1. Test 1: Ventilation grill filter

This filter is a standard ventilation grill filter, intended for application in a ventilation grille above a window. Thus, this filter should be suitable for application with natural airflow. Figure 5.10 shows a picture of this filter type, as found on the web shop.
It is relevant for this research to know what the performance of such a filter is, to be able to say something about the performance of a ventilation grill. The research question for this test is:

***'Does a ventilation grill filter provide sufficient protection?***


Figure 5.10 | Photo of the test object: 'ventilation grille filter' | Source: (Webshop: Wtw-filtershop)

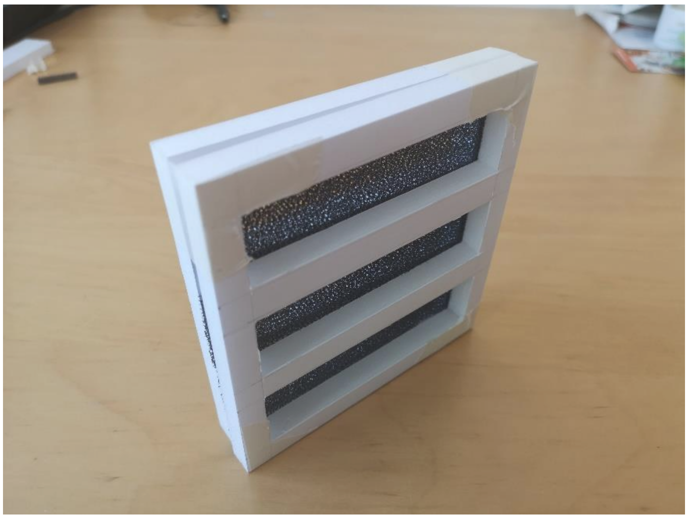


Figure 5.11 | Photo of the test object: ventilation grille filter | Source: own work

***Results***

The raw data is presented in Appendix I. The values derived from the graphs are presented in table 5.B. For three different particle sizes and three different wind speeds data is collected.

| Data: 'Ventilation grill filter: variant I' Test: 1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air flow | | | Amount of PM | | | | | |
| | | | Before filter | | | After filter | | |
| Power [W] | Wind velocity (empty) [m/s] | Wind velocity (filter) [m/s] | PM1.0 [μg/m3] | PM2.5 [μg/m3] | PM10 [μg/m3] | PM1.0 [μg/m3] | PM2.5 [μg/m3] | PM10 [μg/m$^3$] |
| 4 | 1.7 | N/A | 2600 | 3400 | 3600 | 2400 | 2800 | 2800 |
| 7 | 3.3 | 1.6 | 1900 | 2200 | 2300 | 1600 | 1700 | 1800 |
| 12 | 4.8 | 1.75 | 1600 | 1800 | 1900 | 900 | 1000 | 1000 |

Table 5.B | Data derived from testing the ventilation grille filter | Source: own work

This data was then converted to the pressure drop and performance and is shown in table 5.C.

| Results: 'Ventilation grill filter: variant I' | | | | |
|---|---|---|---|---|
| Pressure drop | | Performance [%] | | |
| Power [W] | Pressure drop [Pa] | PM1.0 | PM2.5 | PM10 |
| 4 | N/A | 8 | 18 | 22 |
| 7 | 1.8 | 16 | 23 | 22 |
| 12 | 5.8 | 44 | 44 | 47 |

Table 5.C | Data from testing the ventilation grille filter converted to the pressure drop and the performance | Source: own work

***Conclusion***

According to the measurements the performance of this filter is especially good at higher wind speeds. At the highest wind speed this filter filters more than 40% of all particulate matter. At low wind speeds the performance is more than halved. The highest performance is 23% then with an average around 15%.
Since the wind speed through a ventilation grille filter is normally low, the ventilation grille offers insufficient protection.

### 5.3.2. Test 2: G4 filter

This type of filter is an fibrous filter designed for pre- or coarse filtration of the air intake in general ventilation and air handling systems, forced air convectors, window ventilation units and small air conditioners. See figure 5.14 for a photo of this filter.
It is typically used in conjunction with a mechanical airflow.

Figure 5.12 | Photo of fibrous filter, which can be bought in the webshop 'WTW-filtershop' and is widely used in air handling units | Source: (Webshop: Wtw-filtershop)

This filter cloth was chosen as a reference to apply as a filter roll in the design of case study one in Chapter 8.
The testing of this filter fabric aims to validate whether this filter fabric is suitable when using natural airflow and what the performance is in such a case.
In this way, an answer can be given to the question:

***'Can this material be used as a reference for the design in the case study?'***

According to the manufacturer where this filter cloth is ordered it should have the properties as mentioned in table 5.D.

| | |
|---|---|
| Performance | Classification: EN 779 G4 - Coarse 60% ISO 16890 |
| Dust holding capacity | 460 g / m$^2$ |
| Pressure drop | 42 Pa |
| Thickness | 20 mm |

Table 5.D | Properties of the G4-filter according to the manufacturer | Source: own work

Because according to the data the original filter cloth is 20mm thick and that would have a pressure drop of 42 Pa it was decided to test the filter cloth with a thickness of 10 mm. Therefore the filter cloth had to be halved first.

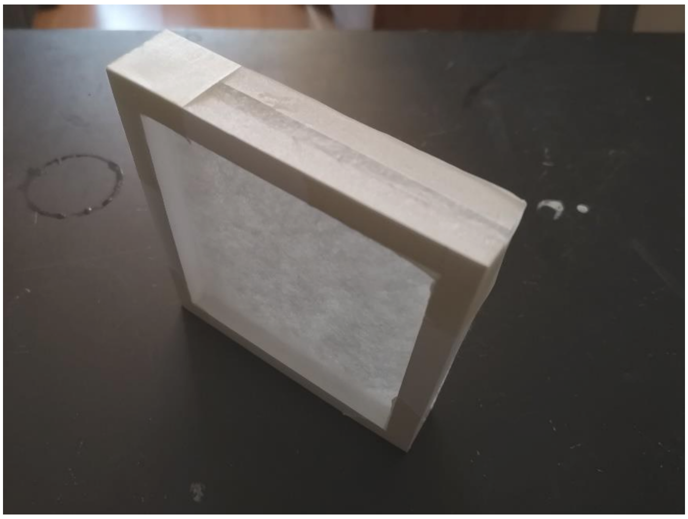


Figure 5.13 | Photo of the test object: G4 filter | Source: own work

### Results

The values derived from the graphs are presented in table 5.E. For three different particle sizes and three different wind speeds data is collected.

| Data: 'G4 filter variant: I' Test: 1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air flow | | | Amount of PM | | | | | |
| | | | Before filter | | | After filter | | |
| Power [W] | Wind velocity (empty) [m/s] | Wind velocity (filter) [m/s] | PM1.0 [µg/m3] | PM2.5 [µg/m3] | PM10 [µg/m3] | PM1.0 [µg/m3] | PM2.5 [µg/m3] | PM10 [µg/m$^3$] |
| 4 | 1.7 | N/A | 3300 | 4500 | 5500 | 2700 | 3200 | 3500 |
| 7 | 3.3 | 0.6 | 2800 | 3300 | 3800 | 2100 | 2300 | 2400 |
| 12 | 4.8 | 1.3 | 1750 | 2000 | 2150 | 1700 | 1850 | 1900 |

Table 5.E | Data from testing the 'G4 filter' converted to the pressure drop and the performance | Source: own work

This data was then converted to the pressure drop and performance and is shown in table 5.F.

| Results: 'G4 filter variant: I' | | | | |
|---|---|---|---|---|
| Pressure drop | | Performance [%] | | |
| Power [W] | Pressure drop [Pa] | PM1.0 | PM2.5 | PM10 |
| 4 | N/A | 18 | 29 | 36 |
| 7 | 4.6 | 25 | 30 | 37 |
| 12 | 7.7 | 3 | 8 | 12 |

Table 5.F | Data from testing the 'G4 filter'converted to the pressure drop and the performance | Source: own work

### Conclusion

By halving the material, the pressure drop indeed appears to be low enough to get a good airflow through the filter. The filter cloth can therefore be used in a system with a natural air flow.

At low wind speeds, the performance of this type of filter is significantly better than the ventilation grille filter as presented in Section 5.3.1.
The results for the highest wind speed have proven to be unreliable due to recirculated air or unknown cause, so nothing can be said about them. It is expected that at the highest speed the filter would perform best.

## 5.4 Interpretation of the results

The results are read by drawing a line, which is an estimate of the average of the results. This line is also an indicator of the reliability of the result.

If this line is a horizontal line, such as in figure 5.14, that means that the air that passes the PM meter has a constant air flow with the same amount of particles in it. Since the air speed and direction of the air flow don't change during the measurement, this should remain the same.

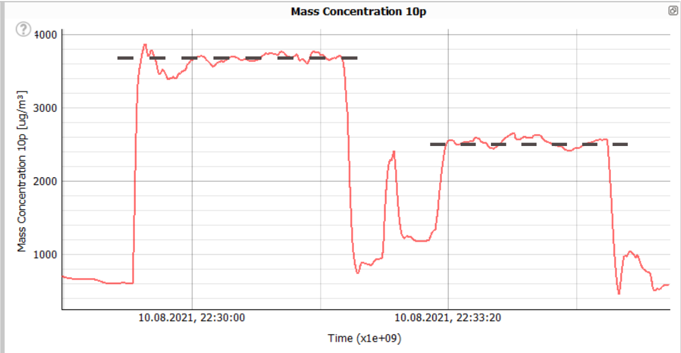



Figure 5.14 | Example of a measurement result from the 'G4 filter' with the averages of the peak before the filter and the peak after the filter indicated as black dotted lines | Source: own work

If this line runs diagonally upwards, such as in figure 5.15, this is an indicator of contamination of the measuring instrument or of recirculation of the same contaminated air.

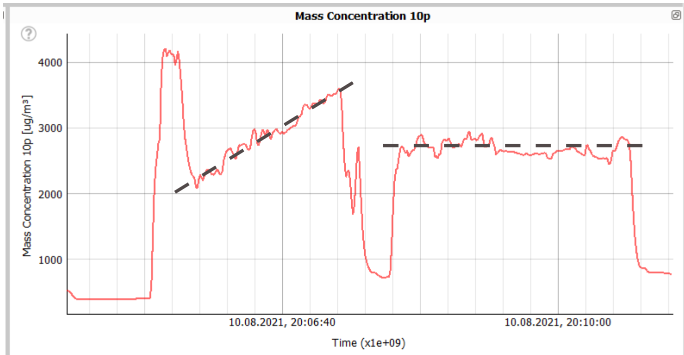



Figure 5.15 | Example of a measurement result from the 'G4 filter' which appears to be unreliable | Source: own work

Reasons for this recirculation of air might be that the PM meter is not placed in a completely laminar air flow. When the air flow becomes turbulent particles might recirculate from the outlet of the PM meter into the inlet again.

Since it's hard to predict how the air flow moves through the tube, it's hard to say whether a measurement is going to be reliable. Only from the results a conclusion can be drawn.

# Conclusion

In this Chapter two tests have been conducted, one on a 'Ventilation grille filter' and one on a 'G4 filter' to answer the two research questions.

- ***Is it possible to test filters at home for their per formance and pressure drop?***

***The set-up***
The set-up described in this chapter is easy to make at home with relatively few supplies. Most of the equipment is cheaply available and can be purchased for use at home.

***Measuring the performance***
To a certain extent the results can be used to say something about the performance of the filter objects. The accuracy of the PM meter was good enough for this. However, the tests are not reliable enough to determine an absolute value for the performance of the filter, because the air flow was difficult to predict and therefore it was often difficult to perform a correct measurement. However, it did prove possible to compare different filters and variants.

***Measuring the pressure drop***
The anemometer was not accurate enough for the low wind speeds in the tube. It was therefore not possible to determine the pressure drop at low wind speeds. For this a lab setup with a pressure gauge is better. Only for high wind speeds an estimate of the pressure drop has been made.

- ***How can the test results support the design?***

The most important question that can be answered is if, under the conditions of the test, the air flows through the filter material at all. If this is measured with the anemometer or determined by hand, it can be stated that the material is suitable for use in a system with a natural air flow.

By comparing different variants, a preference can be expressed to prefer one particular variant over another when designing a concept.

# 6

# Design criteria

The concept designs in this study are designed within a certain context. This framework is formed by the boundary conditions and the corresponding hard criteria. It must be made plausible that a concept meets these hard criteria, otherwise the concept must be improved.

In order to compare the different concepts with each other, soft criteria are created. Together they form a list of qualities for which a concept can get a score from 1 to 3, the higher the better.

In this chapter the boundary conditions, hard criteria and soft criteria are explained.

- ***6.1 Boundary conditions***

In this paragraph, the boundary conditions are described which consist of the climate conditions and the building regulations

- ***6.2 Hard criteria***

The hard criteria are presented in this section

- ***6.3 Soft criteria***

The soft criteria are presented in this paragraph

## 6.1 Boundary conditions

The boundary conditions are related to the *type* of building and the *location* of the building. In this research, they were determined for a high-rise residential building in Rotterdam. This is because this building type and location fit the focus of this research. Also, the case study in this research was conducted on the Montevideo, a high-rise building in Rotterdam.

### 6.1.1. Climate conditions

The limit of the maximum pressure drop is partly determined by the speed at which the wind falls on the façade. For this research, the wind conditions are therefore the most important factor. Another factor is the average outside temperature, which is important to ensure thermal comfort.

***Wind speed***

The monthly wind speeds in Rotterdam are shown in the graph in figure 6.1. It is noticeable that in the summer and the off-season the wind speed is usually 5.5 m/s.
In the winter months, November through February, the wind speed varies a bit more per day and is on average 8.1 m/s. Averaged over the year, the wind speed would then be around 6.4 m/s.
According to the National Energy Atlas, the wind speed at 100 meters is 6.5 to 7 m/s.
These wind speeds apply to open terrain. When a building is in an urban environment, wind speeds lower to the ground will be less because the wind is blocked by other buildings.
When the values above are combined with the influence of the urban environment, it can be roughly assumed for this study that the wind speed will average 5 m/s over the entire building height.

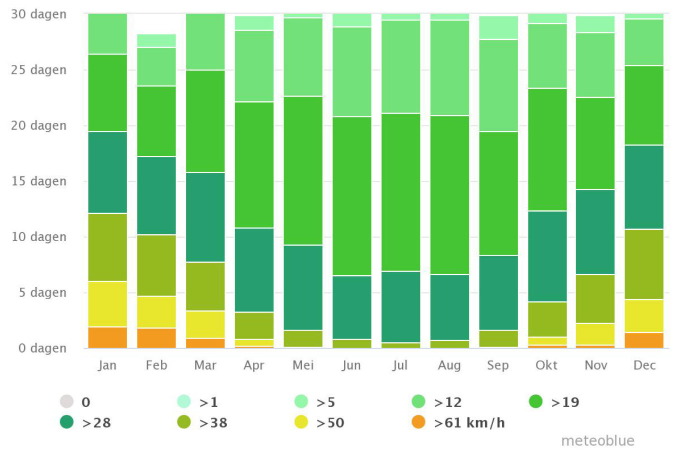



Figure 6.1 | Graph with the average wind speeds of the past 30 years per month | Source: (Meteoblue, 2021)

***Wind direction***

The direction that the wind comes from on average each year is shown in figure 6.2. This clearly shows that the dominant wind direction is southwest. As a result, the southwest façade of a building in Rotterdam will catch the most wind and will also be exposed to the largest pressure difference between inside and outside, namely around 20 Pa.
At the leeward facades of the building, on the other hand, the wind is mainly sucked in mechanically and the pressure differences across the facade will be smaller.
With no wind at all, the maximum pressure difference on the building will be provided by the mechanical exhaust and this can be up to a maximum of 10 Pa.

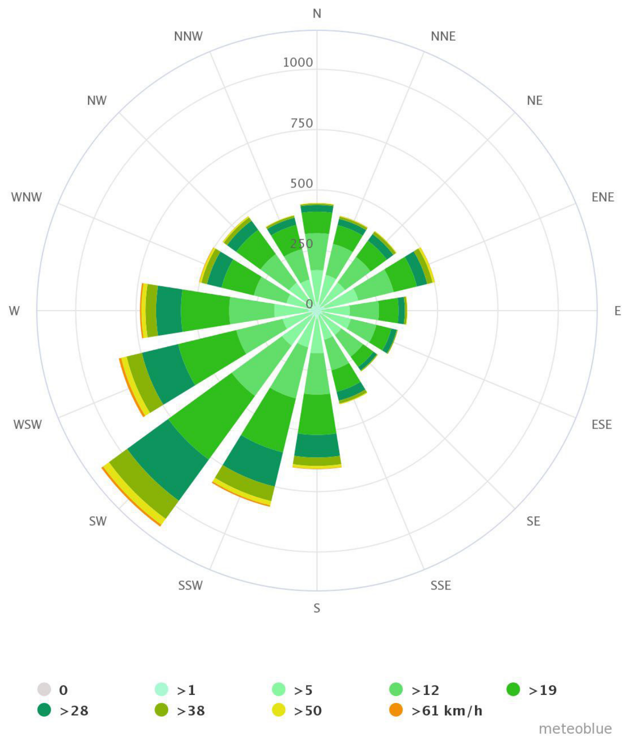



Figure 6.2 | Graph with the average wind direction | Source: (Meteoblue, 2021)

***Temperature***

In the winter months, the temperature is between 1 and 10 degrees Celsius and in the summer months between 10 and 23. The average temperature in the winter is 7 °C and in the summer 21 °C.

### 6.1.2 Building regulations

***General***

The relevant regulations that the design must conform to according to the Dutch Building Regulations can be summarized as follows:

- The thermal resistance (Rc-value) of the facade must be at least 3.5 m^2*K/W
- The building must be protected against sunlight

and heating
- Cold bridges must be avoided
- Minimum sound insulation of 20 dB for an exter nal partition construction of a domestic area
- The partition construction between inside and outside must be watertight
- The facade construction must meet the structur al requirements

***Fire safety***
Fire safety is regulated according to European standards in NEN-EN 13501-1&2. A material used in the facade is classified from A1 to F, as shown in table 6.A. The materials in the facade must at least comply with class A1, A2 or B.

| | |
|---|---|
| A1 | Non-flammable |
| A2 | Practically non-flammable |
| B | Flammable, but very hard to set on fire |
| C | Flammable |
| D | Flammable, very easy to set on fire |
| E | Very flammable |
| F | Not been tested yet and therefore prohibited to use |

Table 6.A | The different fire classes that materials can have according to the norm 'NEN-EN 13501-1&2' summarized in a table | Source: own work

Another point of concern with regard to fire safety is that the fire must not spread from floor to floor through the facade. Where there is a continuous cavity or shaft between different floors, measures such as fire barriers must be taken.

***Ventilation***
- Article 3.29: for an occupied area of a residential function a prescribed capacity of 0.027 m3 / s per m2 of floor area is assumed.
- The wind velocity in accommodation spaces caused by ventilation openings may not exceed 0.2 m/s to prevent discomfort from draught

## 6.2 Hard criteria

The hard criteria include the pressure drop and the dimensions of the structure, which are evaluated with a color code. Green means that the concept is highly likely to meet the criterion, orange means it is doubtful and red means it is insufficient.
In table 6.B the criteria for the pressure drop and the dimensions are summarized.

| Hard criteria | |
|---|---|
| **Pressure drop** | ● < 20 Pa, most likely<br>● Close to 20 Pa, or not sure if it is below<br>● Very little chance that it is below 20 Pa |
| **Dimensions** | ● Height: fit between floors Width: 1,2m / 1,5m According to commonly used sizes<br>● It fits, but unusual sizes<br>● Doesn't fit in a facade |

Table 6.B | The hard criteria and the definition of the three color codes | Source: own work

### 6.2.1. Pressure drop

The maximum pressure drop is determined by the maximum pressure difference over the façade. The maximum pressure difference is determined by the wind pressure on the outside and the pressure in the interior. The maximum pressure difference can be calculated using the following formula:

$$\Delta P_{max} = P_{wind} - P_{room}$$

In order to let air flow through the opening and air purification system in the façade the pressure drop of the system should always be lower than the maximum pressure difference on the façade.

***Wind pressure***
The wind pressure on the façade depends on factors such as the orientation of the surface, the reference point of the wind velocity and the amount of wind cover around the building. All those factors are combined in a location dependent coefficient Cp, which is assumed for this research to be 0.6.
The wind pressure on the façade can be estimated with the following formula, which is based on the dynamic pressure formula:

$$P_w = \frac{\rho * V_H^2}{2} * C_p$$

with:
$P_w$: Wind Pressure [$P_a$]
$C_p$: Pressure Coefficient
ρ: Air Density [kg/m$^3$]

v: Wind speed [m/s]

The mean temperature in the Netherlands is about 11 degrees, which gives an air density of about 1.25 [kg/m³ ] and the mean value of the wind velocity [$V_H^2$] is 5 m/s. The wind pressure on the façade is likely to be about:

$$P_w = \frac{1.25 * 5^2}{2} * 0.6 = 9.38 \left[\frac{kg}{m * s^2}\right]$$

This can be rounded up to 10 Pa, which is the maximum wind pressure that can be caused by the wind on the building at a height of 100 m.

***Pressure in the room caused by the mechanical exhaust***
For this study, it is assumed that the room can be brought to a maximum of 10 Pa negative pressure with mechanical extraction compared to the outside.

***Conclusion***
Assuming a situation *with* wind:

$$\Delta P_{max} = P_{wind} - P_{room}$$

$$\Delta P_{max} = 10 - (-10)$$

$$\Delta P_{max} = 20$$

The max pressure drop is then:

$$\Delta P_{pressure\ drop} < 20\ Pa$$

Assuming a situation *without* wind, the max pressure drop is then:

$$\Delta P_{max} = 0(-10)$$

$$\Delta P_{pressure\ drop} < 10\ Pa$$

## 6.3 Soft criteria

In order to compare the different concepts with each other, soft criteria are created. Together they form a list of qualities, see table 6.C, for which a concept can get a score from 1 to 3, the higher the better.
The qualities are organized into four groups: *air treatment, design qualities, constructability* and *maintenance*.

### 6.3.1 Air treatment

***Filter quality***
The filter quality says something about the performance of a filter in relation to the pressure drop that is required for this.

For the filtering of *nitrogen dioxide* the pressure drop is usually insignificant, because the coating is usually on the surface of a wall panel. So here only the performance is considered. The limit value here is set at 50%, which is based on the usual classification for filters. If a filter scores higher than this value, it receives a score of 3, regardless of the pressure drop.

When filtering *particulate matter* the pressure drop does play a major role. In this research it is stated that the maximum pressure drop may be 20 Pa. How well a filter filters fine dust is indicated by the usual classification for particulate filters, as explained in section 2.3.2.

In this case it means that if a filter filters at least 50% of particles with a minimum size of 2,5 µm at a pressure drop of 20 Pa or less, it receives a score of 2.

***Thermal comfort***
In the climate of Rotterdam the outside air is too warm in summer and too cold in winter to be ventilated directly without having to cool or heat the building in some way. In order not to increase the cooling load or the energy required for heating, it is important that the air is preheated in winter and cooled in summer before it is used to ventilate the building.

***Air circulation***
Air circulation says something about how well the incoming air mixes with the air in the room. Proper air circulation is important for building comfort. Here the location where the air enters the room is important and the type of opening that is used, as explained in paragraph 4.1.
In cold climates it is better to bring the air in at a high position in the façade and in warm climates a low position is more desirable.
The type of opening should not be too large and should have some pressure drop to prevent wind from outside from blowing into the building. The smaller the opening and the more dispersed the openings are placed in

the facade the better the air circulation will be the less chance of drafts.

### 6.3.2 Design qualities

***Acoustics***
When an air flow is created in a structure, it is important that the air does not produce whistling sounds.
When designing ventilation openings in the facade, the sound from outside must be excluded as much as possible to prevent nuisance. A ventilation opening can quickly undo the sound absorption of the rest of the façade if no sound attenuation measures are taken in the opening. It is therefore important that either in the ventilation opening, or elsewhere in the construction, there is a possibility to take sound-absorbing measures.

***Design flexibility***
Since the solutions in this study are intended to provide occupants of high-rise buildings with better air quality, it is also important that the designs offer freedom for the occupant himself to be able to influence the design. After all, these are facade designs that also affect the aesthetics inside.
The criteria here are based on the amount of freedom the resident has to have a say or change something in the design.

### 6.3.3 Constructability

***Suitability for renovation project***
In order to provide existing buildings with better air, it is important that the design is suitable to be applied in an existing building. This involves determining which parts of the existing building need to be changed or replaced.

***Building speed on site***
To keep the building costs low it is important that the design can be built quickly. A distinction is made between whether the construction can be done in one go or whether it must be assembled piece by piece on site.

### 6.3.4 Maintenance

***Maintenance frequency***
The maintenance frequency for filters that filter particulate matter is largely determined by the dust holding capacity as explained in section 2.3.1. If a filter can store a relatively large amount of particulate before it becomes clogged, the maintenance frequency will also be lower. The lower the maintenance frequency the better, since high buildings are often difficult to reach for maintenance personnel
It is undesirable if a facade has to be maintained several times a year, especially if the component is only accessible from the outside.

***Maintenance effort***
When a facade panel does require maintenance, it is important that this takes little time. An important distinction here is whether the component is accessible from the inside or only from the outside.

| | |
|---|---|
| **Air treatment** | |
| **Filter quality $NO_2$** | **1.** Performance:<br>< 50%<br>**2.** Performance:<br>>>50%<br>**3.** Performance:<br>>> 50% |
| **Filter quality PM** | **1.** Classification:<br>ISO ePM10 / coarse<br>Pressure drop: > 20 Pa<br>**2.** Classification:<br>ISO ePM2,5<br>Pressure drop: around 20 Pa<br>**3.** Classification:<br>ISO ePM1<br>Pressure drop: < 20 Pa |
| **Thermal comfort** | **1.** No measures taken to cool or heat air<br>**2.** Can only cool or only heat air<br>**3.** Can both cool and heat air |
| **Air circulation** | **1.** Location: wrong regarding climate conditions<br>Opening type: too big or too low pressure drop<br>**2.** Location is good but opening type is not good or the other way around<br>**3.** Location: right spot regarding climate conditions<br>Opening type: smaller openings with enough pressure drop to prevent draft |
| **Design qualities** | |
| **Acoustics** | **1.** No possibilities for improving sound attenuation / Risk that air flow in system causes noise<br>**2.** Some possibilities for improving sound attenuation<br>**3.** A lot of possibilities for improving sound attenuation |
| **Design flexibility** | **1.** The design contains little or no freedom to be adapted to the user's wishes<br>**2.** Parts of the design can be adapted to the wishes of the user<br>**3.** The design can be adapted almost entirely to the wishes of the user |
| Constructability | |
| **Suitability for renovation project** | **1.** All existing parts have to be removed or adapted<br>**2.** Parts of the existing façade have to be removed and adapted<br>**3.** Only one part is replaced or adapted |
| **Building speed on site** | **1.** The structure has to be build part by part on site<br>**2.** Parts of the structure are prefabricated and can be installed immediately on site<br>**3.** The whole structure is prefabricated and can be installed on site |
| Maintenance | |
| **Maintenance frequency** | **1.** Multiple times a year<br>**2.** No more than once a year<br>**3.** No maintenance during lifetime only accidentally |
| **Maintenance effort** | **1.** Parts can only be replaced from outside the building and cost a lot of time.<br>**2.** Parts can be replaced from inside, but cost a lot of time to replace or parts can be replaced from outside very fast<br>**3.** Parts can be replaced from inside very fast |

Table 6.C | The soft criteria with the explanation of the scores from 1 to 3 | Source: own work

# 7

# Concepts:
# Development and analysis

In this Chapter the concepts are presented. The research questions in this chapter is as follows:

- ***How did the different concepts develop?***
- ***How do the different concepts relate to each other?***

First the concepts are presented and every one of them the following sub questions are answered:

- *What design choices underlie this concept?*
- *How can the concept be analyzed?*
- *What instructions apply in developing this concept into a product?*

- ***7.1 Explanation of the concepts***

In this paragraph it is explained what the *design choices* are, how the concepts are *analyzed* and what the *instructions* are.

The concepts are as follows:

- ***7.2 Cyclone separator with PCO***
- ***7.3 Biofacade: Living Wall System (LWS)***
- ***7.4 Biofacade: Active Green Wall (AGW)***
- ***7.5 Outside filter box variant I***
- ***7.6 Outside filter box variant II***
- ***7.7 Inside filter box***

Then in the conclusion the different concepts are presented in the Quality table, which makes it possible to compare them with each other.

## 7.1 Explanation of the concepts

In this paragraph it is explained what the *design choices* are, how the concepts are *analyzed* and what the *instructions* are.

### 7.1.1 Explanation of the concepts

The choices underlying the concepts can be summarized in three themes: the *air purification technologies*, *the ventilation principle*, and the *construction*.

***Air purification technologies***

For each concept, one or more air purification technologies have been selected. Often technologies can complement or reinforce each other, which is why multiple technologies are selected. In order to filter both particulate matter and $NO_2$, multiple technologies are usually required.

The technologies that can be chosen from are: PCO, Bio-facade (LWS), Biofacade (AGW), Cyclone separator and Fibrous filter. These technologies are explained in more detail in Chapter 3.

***Ventilation Principle***

The ventilation principle of a concept is based on two choices: direct or indirect and concentrated or distributed.

Direct or indirect refers to whether or not the concept transports outside air directly into the interior space. With an *indirect* ventilation principle, the air passes through the structure where it is filtered, but must then still be brought into the space through a cavity or other ventilation opening in the facade.

A concept with a *direct* ventilation principle on the other hand is more integrated with the rest of the facade and will transport the air directly into the interior space.

With a *concentrated* airflow, the air is blown out of the structure through only a few ventilation openings, while with a *distributed* airflow it is blown more evenly over the surface of the structure.

The application of ventilation principles is based on the literature review in chapter 4.

***Construction type***

The construction of the concept is based on whether it is an integral module or an exterior panel.

The *integral* facade design runs through all the layers of the facade. This is usually accompanied by the choice of direct air flow.

The *exterior panel,* on the other hand, is a stand-alone structure relative to the façade.

The relevant structures for this study are summarized in Chapter 4

All these choices are summarized in table 7.A. For each of the concepts this table can be filled in so that it is clear which choices underlie the concept.

| **Air purification technology** | **Ventilation** | | **Construction** |
|---|---|---|---|
| PCO | Direct | Concentrated | Integral module |
| Bio-facade: LWS | Indirect | Distributed | Exterior panel |
| Bio-facade: AGW | | | |
| Cyclone separator | | | |
| Fibrous filter | | | |

Table 7.A | Overview of the design choices in general | Source: own work

## 7.2 Cyclone separator with PCO

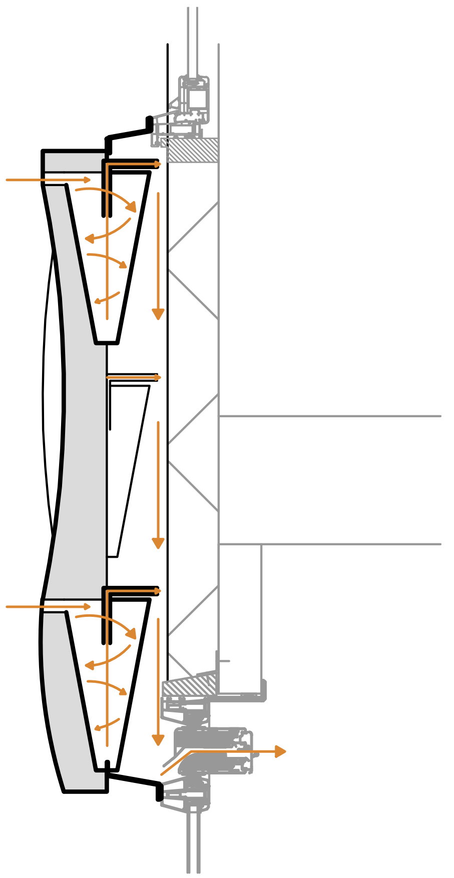


Figure 7.1 | Section of concept: 'Cyclone separator with PCO'. The orange arrows indicate the air flow through the system | Source: own work

This concept consists of a panel system where air is filtered with PCO and cyclones, which can be attached to an existing structure, see figure 7.1.

### 7.2.1 Design choices

The design choices for this concept are shown in table 7.B. The explanation follows below.

| Air purification technology | Ventilation | | Construction |
|---|---|---|---|
| PCO | Direct | Concentrated | Integral module |
| Bio-facade: LWS | Indirect | Distributed | Exterior panel |
| Bio-facade: AGW | | | |
| Cyclone separator | | | |
| Fibrous filter | | | |

Table 7.B | Overview of the design choices of the concept: 'Cyclone separator with PCO' | Source: own work

#### *Air purification technology*

In this concept, two filter technologies were applied: *Photocatalytic oxidation with $TiO_2$ (PCO)* and *Cyclone filters*. The first to filter $NO_2$ and the second to filter particulate matter from the outside air.

In this design, the use of PCO goes well with the cyclones because they provide an erratic shape to the panel. This shape creates the necessary air turbulence, which benefits the performance of the PCO.

Two options are available for the application of PCO. Since the design of the panel lends itself to being made of (lightweight) concrete, the catalyst can be mixed into the concrete mixture and produced in a single pass in a mold. The other option is for the $TiO_2$ to be applied to the panel as a coating.

The cyclones are placed in recesses on the inside of the panel. This was done mainly for aesthetic reasons, but also to prevent the cyclones from becoming dangerous protruding objects.

#### *Ventilation principle*

First, air flows along the panel and will be able to swirl due to the shape and material of the panel to come into additional contact with the catalyst $TiO_2$. Then the outside air is collected through the openings in the concrete panel, after which it enters the cyclone through a tube. Through a vortex motion, which provides for the filtering of particulate matter, the air is then blown out of the panel through the cyclones' exhaust. All the exhausts together, which are scattered throughout the panel, then cause a *distributed air flow* in the cavity.

In this example, the air is blown into a cavity, so the ventilation principle of this design is *indirect*. A direct air flow could be made when all the tubes exit directly into the interior space.

#### *Construction*

The structure consists of an exterior panel that, in this design, extends to a cavity. The panels are fixed to the supporting structure of the secondary structure behind. The choice for an exterior panel is mainly based on the fact that the design is then more usable in a renovation project.

### 7.2.2 Concept analysis

How the concept was assessed on the various criteria is shown in table 7.C. Below is the explanation of the assessment.

| | Hard criteria | | Air treatment | | | Design qualities | | Construct-ability | | Mainte-nance | | Total score: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dimensions | Pressure drop | Filter quality $NO_2$ | Filter quality PM | Thermal comfort | Acoustic damping | Design flexibility | Suitability for renovation project | Building speed on site | Maintenance effort | Maintenance frequency | |
| CYCLONE SEPARATOR with PCO | ● (green) | ● (yellow) | 2 | 1 | 1 | 1 | 2 | 3 | 3 | 2 | 3 | 18 |

Table 7.C | Quality table of concept: 'Cyclone separator with PCO' | Source: own work

***Hard criteria***
The cyclones can be made in a format that allows them to be fixed in a panel. These panels can be made to standard sizes in facade construction. Since the studies on the operation of cyclones have been carried out with mechanical airflow, it is not certain whether the cyclones achieve a low enough pressure drop to operate with a natural airflow. This will require further investigation.

***Air treatment***
Cyclones work optimally at high wind speeds. When applied at low wind speeds, the performance will therefore by definition be relatively low and the cyclones will only filter out coarse particles.
The filter performance of $NO_2$ by PCO reach an average value of 50%, therefore for filtering $NO_2$ this concept scores well.
In theory the air can be preheated when the cyclones are warmed up by the sunlight and the air is heated inside. This mechanism is expected to play a minor role and can therefore be neglected.

***Design qualities***
Any measures to improve acoustics can be incorporated into the rear vents. The air flowing through the cyclones can theoretically cause noise pollution in the form of whistling sounds.
The panels offer great design flexibility such as the shape and color of the panel in combination with the configuration of cyclones. Also, a configuration can be formed with the panels together.

***Constructability***
Since it is a panel system, which can be attached to a rear structure, this concept is ideally suited for a renovation project. Only the outer shell of the facade needs to be replaced.
The panels can be prefabricated and can therefore be quickly attached at the building site.

***Maintenance***
In case of damage, the panels can only be replaced from the outside. However, this can be done quickly because the entire panel can be replaced at once.
The cyclones can be designed in such a way that they do not need to be replaced or cleaned during the lifetime of the panel, the collection trays should be large enough. The panels themselves also require little maintenance depending on the finish and material.

### 7.2.3 Design instructions

***Design requirements***
- The interconnecting panels should be made as airtight as possible.
- The openings should be detailed so that rainw ter does not beat in and the wind does not sing.
- The shape of the cyclones should be tested for optimum operation at low wind speeds.
- The catch basins should be large enough so that they do not become clogged with particulate matter during the lifetime of the panel.
- The finish of the panel material should preferably be rough for better performance of the PCO.
- For performance optimization, the openings of the cyclones should be placed in the wind as much as possible

***Design parameters***
The design parameters of this concept relate to the box, filter and fixing system. Table 7.D shows the parameters.

| | |
|---|---|
| Panel properties | Geometry |
| | Configuration of cyclones |
| | Material |
| | Color |
| PCO | Coating |
| | In mixture panel |
| Cyclones | Opening size |
| | Opening shape |
| | Geometry |
| | Material |
| | Fixing system to panel |
| Fixing system | Attachment of box to underlying façade structure |
| | Attachment of boxes to each other (airtight) |

Table 7.D | Quality table of concept: 'Cyclone separator with PCO' | Source: own work

## 7.3 Biofacade: Living Wall System (LWS)

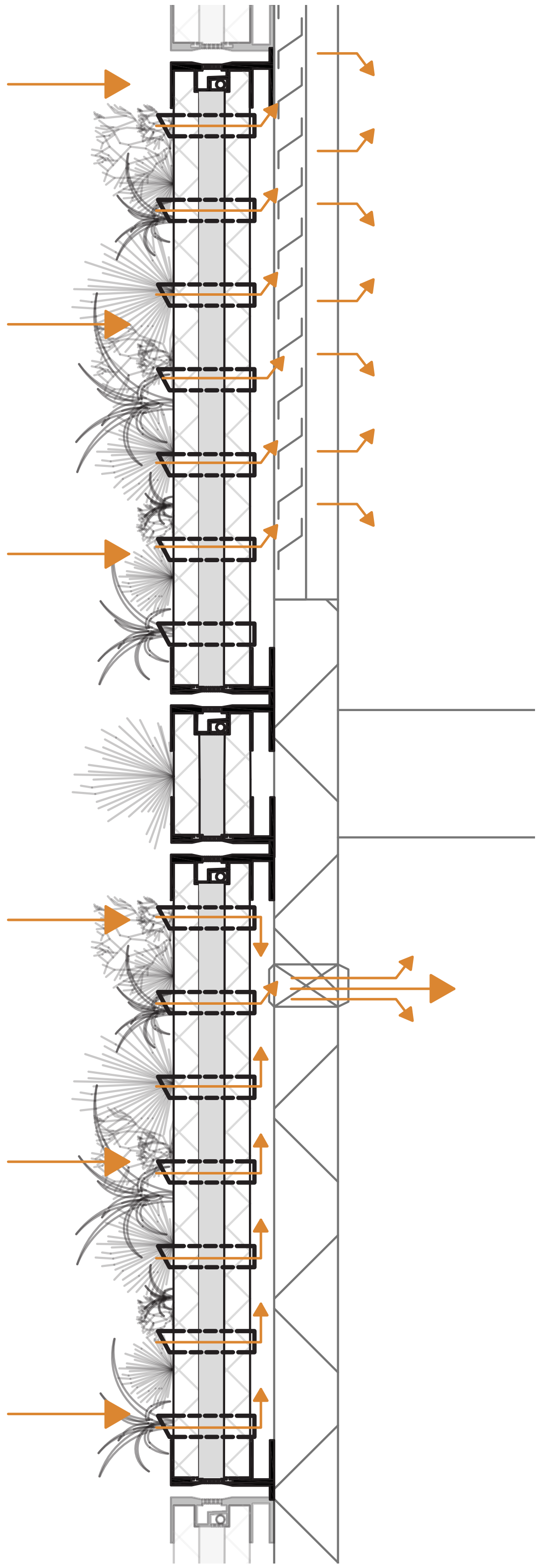


Figure 7.2 | Section of concept: 'Living Wall System'. The orange arrows indicate the air flow through the system | Source: own work

This concept is based on the Living Wall System (LWS) as described in section 3.2. This system consists of panels which contain both insulation and a substrate on which plants can grow. The panels are interconnected with an irrigation channel to provide the plants with moisture and nutrients. Tubes in the panels allow air to pass through the plants and panels into the cavity, where it can flow through the usual ventilation openings into the interior space behind.
The filtering effect of this system is low compared to other concepts, but this concept does score high on average on other qualities.
Figure 7.2 shows a cross section, with the air flow from outside to inside indicated by arrows.

### 7.3.1 Design choices

The design choices for this concept are shown in table 7.E. The explanation follows below.

| Air purification technology | Ventilation | | Construction |
|---|---|---|---|
| PCO | Direct | Concentrated | Integral module |
| Bio-facade: LWS | Indirect | Distributed | Exterior panel |
| Bio-facade: AGW | | | |
| Cyclone separator | | | |
| Fibrous filter | | | |

Table 7.E | Overview of the design choices of the concept: 'Active Green Wall' | Source: own work

#### *Air purification technology*

In this concept only one technology is applied, namely the *Living Wall System (LWS)*. With this system both particulate matter and nitrogen dioxide can be filtered. The LWS is a form of biofacade in which the leaves of the plants provide the filtering effect.
The particulate matter is deposited on the leaves by the mechanical capture mechanisms of the leaves. The air passing through the pores of the leaves is filtered for $NO_2$, as also described in section 3.2.

#### *Air flow*

The outside air first comes into contact with the panel's planting, after which it flows via the leaves and pores through tubes in the insulation layer to the cavity. From the cavity, the air can then be led into the interior through various ventilation openings.
Because the air does not enter the room directly, but through a cavity, there is an *indirect* air flow.
The air flow that goes through the panel is in principle a *distributed* air flow, but it depends on the ventilation opening whether the air entering the room will also be distributed or more concentrated.

#### *Construction*

The construction consists of a panel system, which consists of separate panels that are interconnected. This system falls under the category of *exterior panel*. This means that the degree of integration of the panel with the facade is not high. The panels can easily be attached to the outer layer of the facade.
The panels themselves can be prefabricated and consist of several layers connected together.

### 7.3.2 Concept analysis

How the concept was assessed on the various criteria is shown in table 7.F. Below is the explanation of the assessment.

| | Hard criteria | | Air treatment | | | Design qualities | | Construct-ability | | Mainte-nance | | Total score: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dimensions | Pressure drop | Filter quality $NO_2$ | Filter quality PM | Thermal comfort | Acoustic damping | Design flexibility | Suitability for renovation project | Building speed on site | Maintenance effort | Maintenance frequency | |
| BIOFACADE Living Wall System | • | • | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 14 |

Table 7.F | Quality table of concept: 'Biofacade: Living Wall System (LWS)' | Source: own work

#### *Hard criteria*

The panels are very variable in terms of dimensions and therefore extremely suitable for application in a facade. The only comment that can be made is that the panels are relatively thick and so this should be taken into account in the design.
Because in LWS the air only flows through the leaves and not through the roots, as in the AGW in section 7.4, the pressure drop is low and well below the maximum value.

#### *Air treatment*

The filtering effect of both NO2 and particulate matter is disappointing. When filtering with plants, it is generally the case that a lot of plants are needed to make a significant difference to air quality.
The strength of this system lies mainly in the fact that plants have other qualities besides a filtering effect, such as providing thermal comfort. By evaporating water on their leaves, plants can provide cooling of air in the summer.

#### *Design qualities*

Depending on the density and thickness of the planting, the planting has a positive effect on the acoustic attenuation of the facade because leaves can absorb sound vibrations well.
The design flexibility of a green facade is great, because different plant species can be chosen.

#### *Constructability*

This concept is well suited for a renovation project, as it involves a panel that is attached to the outside of the facade and is separated from the rest of the facade. The only potentially major modification is the fact that the panels must be connected to a water supply in some way.
Apart from this water connection, the panels are completely prefabricated and can be installed on the facade immediately including planting.

#### *Maintenance*

The maintenance of the panels can only be done from the outside. Especially the planting requires the most maintenance. When the panel as a whole no longer functions, it can also be decided to replace it.
Which plants and which substrate is used will mainly determine the maintenance frequency of the concept. In most cases this will be at least annually.

### 7.3.3 Design instructions

#### *Design requirements*

- The system must have a separate water conne tion through the roof or wall
- Rain penetration through the air tubes in the panels must be prevented
- The planting must be suitable for a hydroponic system
- The orientation of the facade with respect to sunlight must be taken into account when deter mining the right plants

#### *Design parameters*

The design parameters of this concept relate to the panel, substrate and plants. Table 7.G shows the parameters.

| | |
|---|---|
| Panel | Geometry |
| | Material |
| | Joint system |
| Substrate | Material |
| | Thickness |
| Plants | Species |
| | Density |

Table 7.G | Design parameters of concept: 'Living Wall System' | Source: own work

## 7.4 Biofacade: Active Green Wall (AGW)

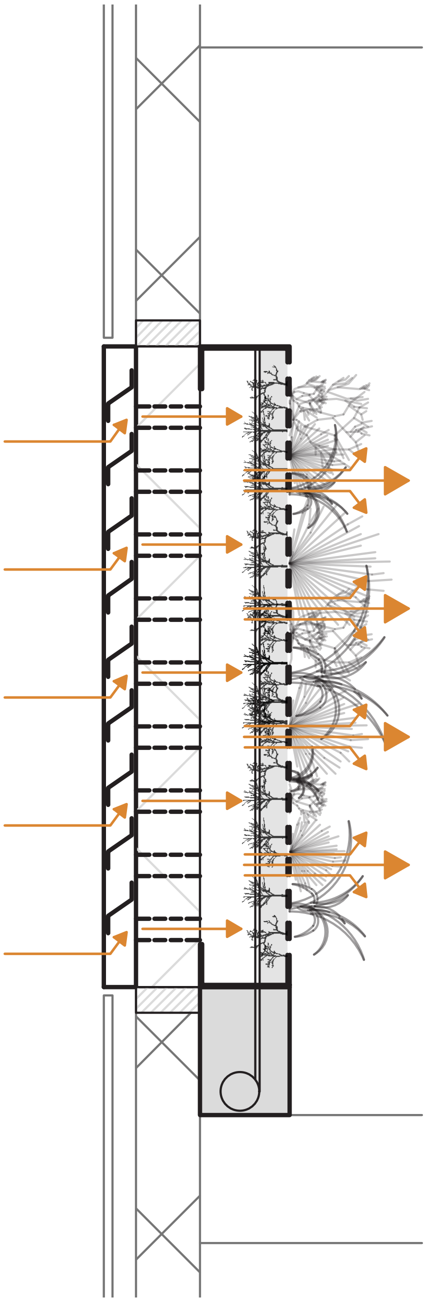


Figure 7.3 | Section of concept: 'Active Green Wall'. The orange arrows indicate the air flow through the system | Source: own work

This concept is based on an Active Green Wall (AGW). This is a system in which air flows through the roots and leaves of plants. In this concept, air enters the AGW through a ventilation opening in the façade and through tubes in the insulation layer, then enters the space through the plants.
Figure 7.3 shows a cross section, with the air flow from outside to inside indicated by arrows.

### 7.4.1 Design choices

The design choices for this concept are shown in table 7.H. The explanation follows below.

| Air purification technology | Ventilation | | Construction |
|---|---|---|---|
| PCO | Direct | Concentrated | Integral module |
| Bio-facade: LWS | Indirect | Distributed | Exterior panel |
| Bio-facade: AGW | | | |
| Cyclone separator | | | |
| Fibrous filter | | | |

Table 7.H | Overview of the design choices of the concept: 'Active Green Wall' | Source: own work

***Air purification technology***

Two technologies were applied in this concept: *Photocatalytic oxidation with TiO2 (PCO)* and the *Active Green Wall (AGW)*.
PCO can be applied to the outside of the panel and is designed to filter $NO_2$. The AGW is located on the inside of the room and is primarily intended to filter particulate matter and, to a lesser extent, $NO_2$.
These technologies complement each other due to the fact that the PCO provides additional filtering of $NO_2$, as the planting in the AGW only minimally filters $NO_2$.
The PCO is applied on the outside and will have to be integrated with the outer panel which is also the ventilation opening. In the case of this concept, this is a ventilation grille. The PCO could be applied as a coating to the metal of this grille, whereby the jagged shape of the grille provides extra surface area and air vortices that enhance performance.
The AGW is placed on the inside of the facade and includes a frame with a substrate on which plants can grow. The roots of the plants grown on the substrate form a kind of fibrous filter, where the roots are the fibers that filter the particulate matter. The leaves of the plants also have a filtering effect to a lesser extent, where the leaves can filter particulate matter and $NO_2$.

***Air flow***

Air flows into the system on the left side through a ventilation opening, such as the ventilation grille. Then the air flows through the insulation layer and then enters the AGW, where it enters the space through the roots and leaves of the plants.
The air flow of this concept is a *direct* air flow, because the air goes directly from the outside through the system into the interior space.
The air is introduced into the space through many different and evenly distributed small holes between the roots of the plants which creates a *distributed* airflow.

***Construction***

The structure consists of three parts that must be connected to each other and which together form an *integral module* that runs through all the layers of the façade.
The outer part consists of a ventilation opening, this can be openings as discussed in section 4.2. A ventilation grille was chosen for this concept.
The middle part consists of the insulation layer, where

holes are made for the air to flow through.
The inner part consists of the AGW, which consists of a cabinet that can be mounted to the insulation material and contains a substrate for plants to grow on.
These three parts can be made and produced separately, but should be matched to each other so that they can be attached together on site to form a single unit.

It is also conceivable that this system could be designed and produced as a module and installed as a whole in the facade. This depends on the attachment of the insulation material and on the type of ventilation opening that is used.

### 7.4.2 Concept analysis

How the concept was assessed on the various criteria is shown in table 7.I. Below is the explanation of the assessment.

| | Hard criteria | | Air treatment | | | Design qualities | | Construct-ability | | Mainte-nance | | Total score: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dimensions | Pressure drop | Filter quality $NO_2$ | Filter quality PM | Thermal comfort | Acoustic damping | Design flexibility | Suitability for renovation project | Building speed on site | Maintenance effort | Maintenance frequency | |
| BIOFACADE Active Green Wall | • | • | 3 | 2 | 3 | 2 | 2 | 1 | 1 | 2 | 1 | 17 |

Table 7.I | Quality table of concept: 'Biofacade: 'Active Green Wall' | Source: own work

#### *Hard criteria*

An Active Green Wall was originally designed as an indoor apparatus, so it has a suitable size to be applied in the facade. The thickness of the panel is not a problem as long as the panel extends inwards.
The pressure drops of the AGW systems as studied in section 3.3 are around 20 Pa. This is mainly dependent on the root density and the plant species applied. In the development of this concept into a product, this should be further investigated.

#### *Air treatment*

The filter performance of $NO_2$ by PCO can reach a height of 70%, while the performance of the planting is around 25%. These effects combined result in a good filter performance of $NO_2$.
With regard to the filtering of particulate matter, this concept also scores high: up to 70% of the particles up to 2.5 µm and up to 90% for particles up to 10 µm are filtered. The relatively high pressure drop of around 20 Pa, however, lowers the filter quality somewhat.
The plants can humidify and cool air. By installing hot water tubes in the cabinet the air can also be pre-heated.

#### *Design qualities*

Green facades are known to have some form of acoustic attenuation.
Which plants are chosen is a big design freedom for the user of the panel and largely determines what the panel will look like inside.

#### *Constructability*

This concept seems unsuitable for a renovation project because it is an integral module that includes all the layers of the facade. An existing facade would have to be modified too much for this system, so it is better to install a new facade with this system.
Since it is a complex system consisting of three parts and also requires planting, the building speed on site will be relatively long.

#### *Maintenance*

The plants in this system require the most maintenance. The possible maintenance of this system will therefore mainly take place on the inside, since this is where the plants are placed. Because of this, the maintenance effort is relatively low because the system is accessible from the inside. However, the maintenance does require knowledge and energy.
The system will require maintenance several times a year.

### 7.4.3 Design instructions

#### *Design requirements*

- The panel should be placed near a window to allow sufficient daylight for planting
- The planting must be carefully chosen
- The three separate parts of the structure should be coordinated with each other
- This system requires great user involvement as the planting requires relatively high maintenance.
- A water connection must be available for this system

#### *Design parameters*

See table 7.J.

| | |
|---|---|
| Ventilation opening | Type |
| | Material |
| | Geometry |
| Insulation layer | Thickness |
| | Material |
| | Configuration of holes |
| Panel | Geometry |
| | Material |
| | Substrate |
| Plants | Species |
| | Density |

Table 7.J | Design parameters of concept: 'Active Green Wall' | Source: own work

## 7.5 Outside filter box: variant I

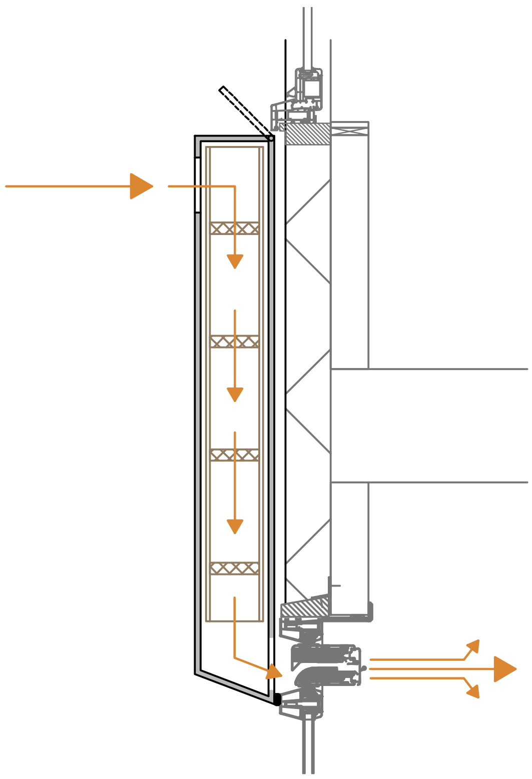


Figure 7.4 | Section of concept: ‘Outside filter box: variant I’. The orange arrows indicate the air flow through the system | Source: own work

This concept consists of a box in which a frame with fibrous filters is placed to filter fine particulate matter. On the surface of the box, PCO is used to filter nitrogen dioxide.
The box offers several options to improve the air quality also in terms of temperature and it offers room to apply sound absorbing materials. See figure 7.4

### 7.5.1 Design choices

The design choices for this concept are shown in table 7.K. The explanation follows below.

| Air purification technology | Ventilation | | Construction |
|---|---|---|---|
| PCO | Direct | Concentrated | Integral module |
| Bio-facade: LWS | Indirect | Distributed | Exterior panel |
| Bio-facade: AGW | | | |
| Cyclone separator | | | |
| Fibrous filter | | | |

Table 7.K | Overview of the design choices of the concept: ‘Outside filter box: variant I’ | Source: own work

***Air purification technology***
In this concept, the technology of *fibrous filters* and *Photocatalytic oxidation (PCO)* is incorporated into a panel system that consists of a hollow box. Inside the box the fibrous filters are placed to filter particulate matter and the outside of the box hosts the PCO, which converts nitrogen dioxide into less harmful substances.

Placing several separate fibrous filters in a row, with a layer of air in between, increases the performance of the individual filters without increasing the pressure drop. This has also been tested and the results are shown in Chapter 6.

***Air flow***
The air enters the box through an air grille in the box and flows through the electret filters to finally leave at the bottom of the box. Since the airflow has to pass through the filters one after another, it leaves the box through a *concentrated* opening at the bottom.
Since this is an extrerior panel, the airflow comes out *indirectly* to, for example, a cavity.

***Construction***
The main construction consists of a hollow cassette in which a sub-construction is placed with fibrous filters. The total construction is mounted as a panel on the outside of the facade, therefore this falls under the category of *exterior panel.*
It is expected that the fibrous filters will need to be replaced annually, therefore the fibrous filters are placed in a frame which can be removed from the box and replaced in its entirety.

### 7.5.2 Concept analysis

How the concept was assessed on the various criteria is shown in table 7.L. Below is the explanation of the assessment.

| | Hard criteria | | Air treatment | | | Design qualities | | Construct-ability | | Mainte-nance | | Total score: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dimensions | Pressure drop | Filter quality $NO_2$ | Filter quality PM | Thermal comfort | Acoustic damping | Design flexibility | Suitability for renovation project | Building speed on site | Maintenance effort | Maintenance frequency | |
| Outside filter box: variant I | ● | ● | 2 | 2 | 2 | 3 | 2 | 3 | 3 | 1 | 2 | 20 |

Table 7.L | Quality table of concept: ‘Outside filter box: variant I’. | Source: own work

***Hard criteria***
Fibrous filters can come in a variety of sizes and are easy to integrate into different structures. The box in this concept can be easily made according to usual dimensions. Many different types of fibrous filters have been introduced to the market. The pressure drop depends on various factors. A pressure drop below 20 Pa is possible with an electret filter if the fiber density is not too high.

***Air treatment***
It is possible to achieve a high performance at a pres-

sure drop of 20 Pa or less. According to van Turnhout et al. (1980) a performance of 98% can be achieved. It is not clear for which particle size this value applies. Also, this value only applies to fibrous filters whose fibers are made of dielectret materials.
The concept offers room for the application of so-called *Phase Change Materials*, which can store the heat from the warm air during the day, so that in the summer the warm air comes in somewhat cooled.

***Design qualities***
It is possible to apply acoustic damping material in the box. The box can be designed as a mass-spring system. Parts of the design can be adapted to the desires of the user, such as the material and the color of the box. The limitation here is that the material must be suitable for the PCO coating. The composition of the type of filters can also be adapted to the situation per box.

***Constructability***
Since it is a panel system that can be attached to a structure behind, this concept is highly suitable for a renovation project.
The panel can be prefabricated so that it can be quickly attached to the underlying insulation material on site.

***Maintenance***
Maintenance of the panels can only be done from the outside and replacing a panel is relatively time consuming.Replacing the filters can be done faster, but requires a lot of logistical planning, because they have to be taken to the building maintenance unit (BMU). As a result, many materials will need to be transported on the BMU and the servicing will take a long time in total.
The electret filters need to be cleaned at least once a year. Since cleaning the filters on site is not possible, this means that the filters will be replaced.

### 7.5.3 Design instructions

***Design requirements***
The design requirements of this concept are as follows:

- The structure must remain accessible on the outside for maintenance personnel to clean the inside of the box and change filters
- The construction of the box must be completely watertight so that the filters remain dry.
- The joint between the box and the underlying insulation material must be detailed so that no moisture can accumulate between them.
- When different types of filters are used, the filters must be placed from coarse to fine, so that the coarser fine dust does not cause the finer filters to clog.
- The total pressure drop must be taken into account when designing the type of filters.
- The material of the filterbox must be suitable for the application of PCO
- The finishing of the material of the filterbox should preferably be rough for a better perfor mance of the PCO.

***Design parameters***
The design parameters of this concept relate to the box, filter, fixing system and type of ventilation openings. Table 7.M shows the parameters.

| | |
|---|---|
| Box properties | Material |
| | Surface roughness |
| | Shape |
| | Color |
| Filter properties | Density |
| | Thickness |
| | Material |
| Fixing system | Box to underlying facade structure |
| | Boxes attached to each other (airtight) |
| Ventilation openings | Top, front |
| | Bottom, back |

Table 7.M | Design parameters of concept: ‘Outside filter box: variant I’. | Source: own work

# 7.6 Outside filter box: variant II

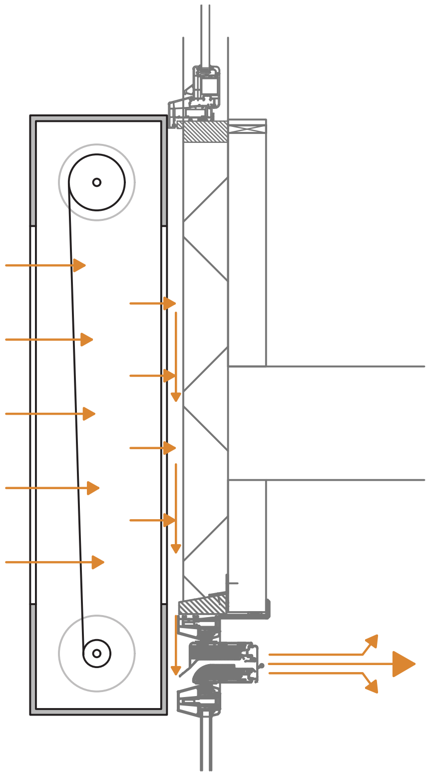


Figure 7.5 | Section of concept: 'Outside filter box: variant II'. The orange arrows indicate the air flow through the system | Source: own work

### 7.6.1 Design choices

The design choices for this concept are shown in table 7.N. The choices underlying this concept are similar to the choices for variant I. The main difference is that the airflow in this concept can also leave the box distributed over the rear panel.

| Air purification technology | Ventilation | | Construction |
|---|---|---|---|
| PCO | Direct | Concentrated | Integral module |
| Bio-facade: LWS | Indirect | Distributed | Exterior panel |
| Bio-facade: AGW | | | |
| Cyclone separator | | | |
| Fibrous filter | | | |

Table 7.N. | Overview of the design choices of the concept: 'Outside filter box: variant I' | Source: own work

***Differences with Variant I***

The choices underlying this concept are similar to the choices for variant I. The main difference is that in this concept the airflow can also be distributed from the box to the structure behind.

### 7.6.2 Concept analysis

How the concept was assessed on the various criteria is shown in table 7.O. Below is the explanation of the assessment.

| | Hard criteria | | Air treatment | | | Design qualities | | Construct-ability | | Mainte-nance | | Total score: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dimensions | Pressure drop | Filter quality $NO_2$ | Filter quality PM | Thermal comfort | Acoustic damping | Design flexibility | Suitability for renovation project | Building speed on site | Maintenance effort | Maintenance frequency | |
| Outside filter box: variant II | ● | ● | 2 | 2 | 2 | 3 | 2 | 3 | 3 | 2 | 2 | 21 |

Table 7.O | Quality table of concept: 'Outside filter box: variant II'. | Source: own work

Since the concept is similar to variant I, only the differences in how the concept is evaluated compared to variant I are mentioned below.

***Differences with Variant I***

The main difference is the maintenance effort of the different variants. In variant I, the filters have to be replaced annually, which is a time-consuming task.
In variant II, the filter cloth can be rotated from one roll to another. The service engineer now only has to continue turning the roll annually. The cabinet does not necessarily have to be opened for this unless a malfunction has occurred in the cabinet. In the event that the cabinets become very dirty inside over time, this could be tested randomly, then the cabinets can be cleaned from the outside. It is expected that this would only need to be done a few times in the lifetime of the panels.

### 7.6.3 Design instructions

***Design requirements***

The design requirements of this concept are as follows:

- The structure must remain accessible on the outside for maintenance personnel to clean the inside of the box and change filters
- The construction of the box must be completely watertight so that the filters remain dry.
- The connection between the box and the un derlying insulation material must be detailed so that no moisture can accumulate between them.
- When using different types of filters, the filters must be placed from coarse to fine, so that the coarser particulates does not cause the finer filters to clog.
- When designing the type of filters, the total pres sure drop must be taken into account.

*Design parameters*

The design parameters of this concept relate to the box, filter, fixing system and type of ventilation openings. Table 7.P shows the parameters.

| | |
|---|---|
| Box properties | Material |
| | Surface roughness |
| | Shape |
| | Color |
| Filter properties | Density |
| | Thickness |
| | Material |
| Fixing system | Box to underlying facade structure |
| | Boxes attached to each other (airtight) |
| Ventilation openings | Top, front |
| | Bottom, back |

Table 7.P | Design parameters of concept: 'Outside filter box: variant II'. | Source: own work

## 7.7 Inside filter box

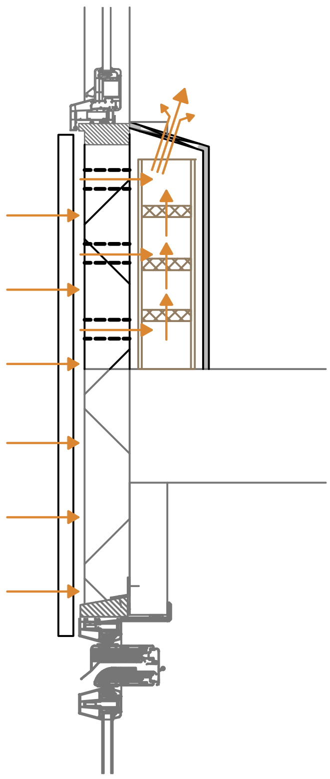


Figure 7.6 | Section of concept: 'Inside filter box', The orange arrows indicate the air flow through the system | Source: own work

### 7.7.1 Design choices

The design choices for this concept are shown in table 7.Q. The explanation follows below.

| Air purification technology | Ventilation | | Construction |
|---|---|---|---|
| PCO | Direct | Concentrated | Integral module |
| Bio-facade: LWS | Indirect | Distributed | Exterior panel |
| Bio-facade: AGW | | | |
| Cyclone separator | | | |
| Fibrous filter | | | |

Table 7.Q | Overview of the design choices of the concept: 'Inside filter box' | Source: own work

*Air purification technology*

In this concept *PCO* can be applied to the exterior panel on the outside of the structure. This can be done by applying a coating or by embedding it in the material. In this way the nitrogen dioxide is partly filtered out of the air.

In this concept, *fibrous filters* are placed in a cabinet on the inside of the facade. Multiple filters are placed in series to capture the particulate matter from large to small. The first filter is a coarse filter to capture the large particles and each subsequent filter is a slightly finer filter to capture the smaller particles. In this way, the finer filters are protected from large particles and are therefore less likely to clog.

*Air flow*

The air is led into the cavity via gaps between the cladding, or via air holes in the cladding. Via a tube through the insulation layer, the air is then led into the filter box. In this filter box, the air is led into the room just below the window frame. Because the air enters the room via a cavity, there is an *indirect* air flow. The air is let in in via a *concentrated* opening.

***Construction***
The construction consists of a composition of three parts: the cladding with the cavity, the insulation material with an air gap and the filter box. This is therefore an *integral module*, because all the parts must be matched to each other.
The filters are placed in the filter box in a frame, so that all filters can be replaced in their entirety if necessary.

### 7.7.2 Concept analysis

How the concept was assessed on the various criteria is shown in table 7.R. Below is the explanation of the assessment.

| | Hard criteria | | Air treatment | | | Design qualities | | Construct-ability | | Mainte-nance | | Total score: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dimensions | Pressure drop | Filter quality $NO_2$ | Filter quality PM | Thermal comfort | Acoustic damping | Design flexibility | Suitability for renovation project | Building speed on site | Maintenance effort | Maintenance frequency | |
| Inside filter box | • | • | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 3 | 2 | 20 |

Table 7.R | Quality table of concept: 'Inside filter box'. | Source: own work

***Hard criteria***
The filter box can be designed for any suitable dimension in a room. However, the thickness of the filter box and the fact that it occupies space under the window must be taken into account.
The pressure drop of this system is largely determined by the fibrous filters. By selecting and designing the fibrous filters in the right way, the pressure drop can remain below 20 Pa.

***Air treatment***
This concept scores an average score for the filter quality of both nitrogen dioxide and particulate matter.
Regarding the thermal comfort this concept scores high, because the filter box is placed inside and is therefore very suitable to be used as a kind of radiator. Inside, the box has easy access to a water or power connection, which can be used to control a heating element.

***Design qualities***
Both in the filter box and in the ventilation opening in the insulation material there are possibilities to apply acoustic damping material.
Both the panel on the outside and the filter box can be designed almost entirely to the wishes of the user.

***Constructability***
In terms of suitability for renovation, this concept does not score high by definition, because it is an integral module. To apply the PCO the outer panel must be customized. For example by applying a coating over the existing panel. Also, a ventilation opening must be made in the current insulation material. The filter box is an addition that is easy to install on the inside of the facade. Because this construction goes through all layers of the facade and cannot be installed in one go, the building speed on site will not be high.

***Maintenance***
Although the filters will probably need to be replaced annually, they are easily accessible from the inside. The occupant could possibly do this himself.

### 7.7.3 Design instructions

***Design requirements***

- Since the air is let in at a non-tactical place in terms of air circulation and drafts, in cold cli mates it is most certainly important to preheat the air in the filter box.
- The filter box should be integrated into the inte rior space and connected to the window frame.
- The material of the panel must be suitable for the application of PCO
- The finishing of the material of the panel should preferably be rough for a better performance of the PCO.
- When different types of filters are used, the filters must be placed from coarse to fine, so that the coarser fine dust does not cause the finer filters to clog.
- The total pressure drop must be taken into ac count when designing the type of filters.

***Design parameters***
The design parameters of this concept relate to the exterior panel, insulation and the filter box.
Table 7.S shows the parameters.

| | |
|---|---|
| Exterior panel | Thickness |
| | Fixing system |
| | Ventilation opening to cavity |
| | Material |
| | Shape |
| Insulation | Thickness |
| | Material |
| | Ventilation opening |
| Filter box | Geometry |
| | Filters |
| | Connection to insulation |
| | Connection to window frame |
| | Ventilation opening to room |
| | Acoustic damping |
| | Heating element |

Table 7.S | Design parameters of concept: 'Outside filter box: variant I'. | Source: own work

# Conclusion

- ***How did the different concepts develop?***

The concepts were made based on three main choices: the *air purification technologies, the ventilation principle* and *the construction type.*

When choosing the *air purification technologies*, it was considered which technologies can be combined well to filter both particulate matter and nitrogen dioxide. Some technologies complement each other so that they function even better together.
The *ventilation principle* was chosen based on whether a direct or indirect air flow is both achievable and preferable. The question of whether the air is brought into the room in a concentrated way or is distributed evenly across the facade also plays a role.
The choice of a *construction type* is mainly based on the extent to which a structure is integrated into the facade. If the structure runs through all the layers of the facade it is called an integral facade construction. When the construction is only placed on the outside of the facade as cladding then it is called an exterior facade panel.

- ***How do the different concepts relate to each other?***

In table 7.T, on the next page, it is presented how the different concepts score on every hard and soft criteria. With this an answer can be given to the sub-question.

In general, the scores of the different concepts are fairly close, especially for the three concepts with a filter box. The Living Wall System comes out worst in the analysis, mainly because the air treatment and maintenance are very weak.
The highest score is obtained by the Outside filter box: variant II, which is elaborated in Case study I.

Most concepts score well on the hard criteria, whereby for two concepts it is not certain whether the low pressure drop is achieved.

The filter qualities of the Active Green Wall are the best, scoring also the only 3 for this criterion.

The acoustic damping is best in the concepts with a filter box.
Every concept can be fairly or well adapted to the user's needs.

How good the constructability of a concept is depends mainly on how much the concept is integrated in the facade. The more it is integrated the worse the constructability in this case. Here are the biggest differences between the different concepts.

For most concepts the maintenance effort is a problem and therefore it is important to keep the maintenance frequency low. However, this is difficult since particulate matter easily accumulates in filters. Also on this point the differences between the concepts are the largest.

| | Hard criteria | | Air treatment | | | Design qualities | | Construct-ability | | Mainte-nance | | Total score: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dimensions | Pressure drop | Filter quality $NO_2$ | Filter quality PM | Thermal comfort | Acoustic damping | Design flexibility | Suitability for renovation project | Building speed on site | Maintenance effort | Maintenance frequency | |
| CYCLONE SEPARATOR with PCO | 🟢 | 🟡 | 2 | 1 | 1 | 1 | 2 | 3 | 3 | 2 | 3 | 18 |
| BIOFACADE Living Wall System | 🟢 | 🟢 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 14 |
| BIOFACADE Active Green Wall | 🟢 | 🟡 | 3 | 2 | 3 | 2 | 2 | 1 | 1 | 2 | 1 | 17 |
| Outside filter box: variant I | 🟢 | 🟢 | 2 | 2 | 2 | 3 | 2 | 3 | 3 | 1 | 2 | 20 |
| Outside filter box: variant II | 🟢 | 🟢 | 2 | 2 | 2 | 3 | 2 | 3 | 3 | 2 | 2 | 21 |
| Inside filter box | 🟢 | 🟢 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 3 | 2 | 20 |

Table 7.T | Table that presents how every concept score on the hard and soft criteria | Source: own work

# 8
# Case Study I: Renovation of the Montevideo

In this chapter, the first Case study of the Montevideo in Rotterdam is presented, assuming a renovation project for the part of the facade with the light grey cassettes, see figure 8.1.
In this Case study, the 'Outside filter box variant I' concept was elaborated for a part of the facade.

The research question for this Case study is:
*How can the concept 'Outside filter box variant I' be developed further for the case of renovating a part of the facade of the Montevideo in Rotterdam?'*

- ***8.1 The Case***
This paragraph provides a brief introduction to the building and the specific facade that is being focused on

- ***8.2 Scenario***
The problem statement, objective, design criteria and design requirements of this case are presented in this paragraph

- ***8.3 Concept selection***
This paragraph presents which concept from Chapter 7 is selected for this Case

- ***8.4 Design plan***
For every design parameter of the concept a goal is determined and a method is presented to achieve this goal

- ***8.5 Design development***
How the concept is worked out according to the goals in the design plan is presented in this paragraph

- ***8.6 Design drawings***
The end result of the Case Study in the form of drawings

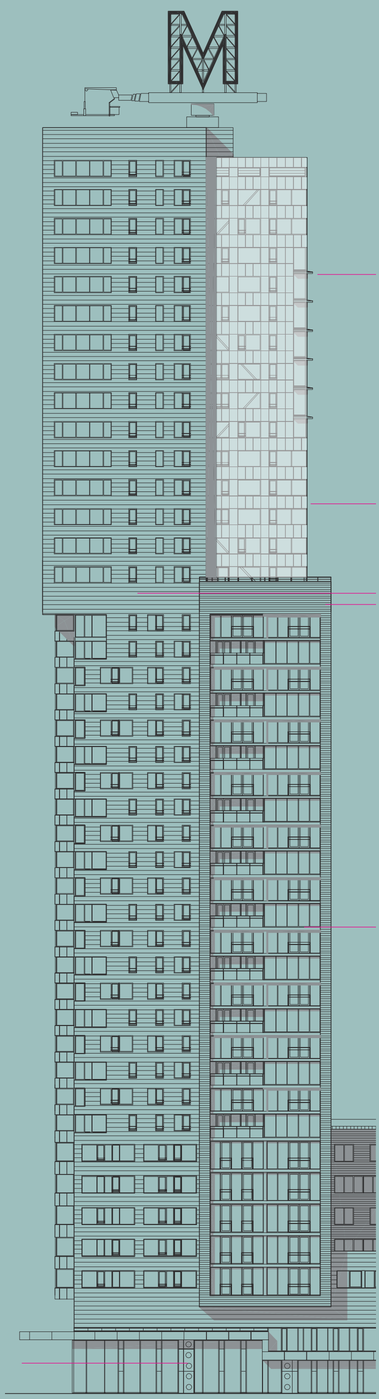


Figure 8.1 | South east front view of the Montevideo with highlighted in white the facade that is focused on in this Case study | Source: Mecanoo, Municipal Archives Rotterdam

## 8.1 The case

The case chosen in this study is the building the Montevideo in Rotterdam, as shown in Figure 8.2.
This building is perfectly suited as a case because it is a high-rise building in an urban area in a developed country. In addition, Rotterdam is also a place where many innovations take place and new things are tried out.
The building is an icon at the 'Kop van Zuid' on the Nieuwe Maas. This makes it a good promotion for innovative developments.

Figure 8.2 | Front view photo of the Montevideo. The light parts of the facade are the light grey cassettes, which are the focus of this case study | Source: (Mecanoo 2021)

### 8.1.1 The facade

The facade focused on in this Case Study is the light grey cassette facade, as shown in the photo in figure 8.3.
The detail drawings of this facade are given in figures 8.4 and 8.5, which form the basis for the renovation drawings.

Figure 8.3 | Close-up of the part of the facade of the Montevideo with the light grey cassettes | Source: (Mecanoo 2021)

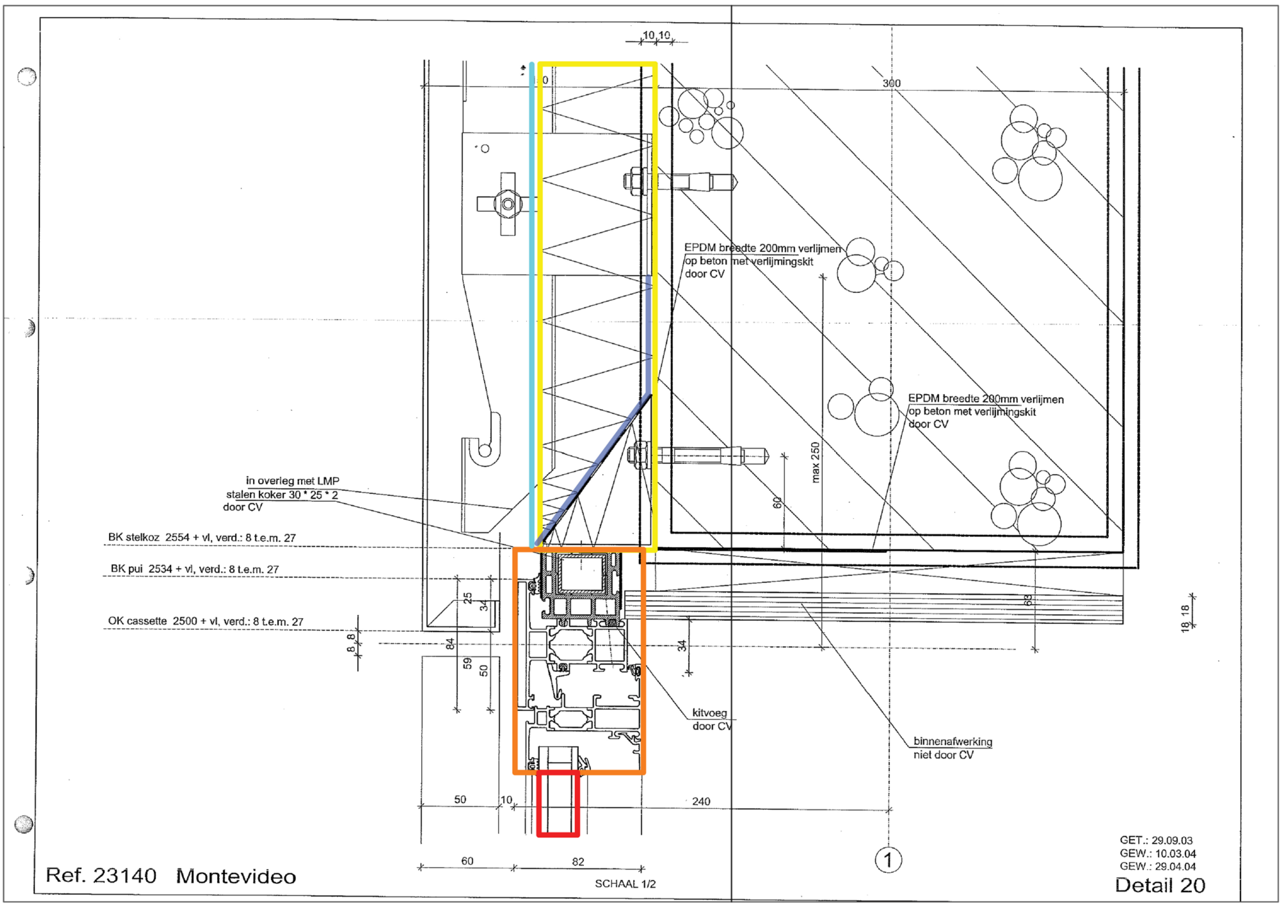



Figure 8.4 | Detail drawing of the upper part of the facade of the Montevideo with the light grey cassettes. Light blue: waterproofing layer. Yellow: the insulation layer. Orange: the window frame. Red: the glazing | Source: Mecanoo, Municipal Archives Rotterdam

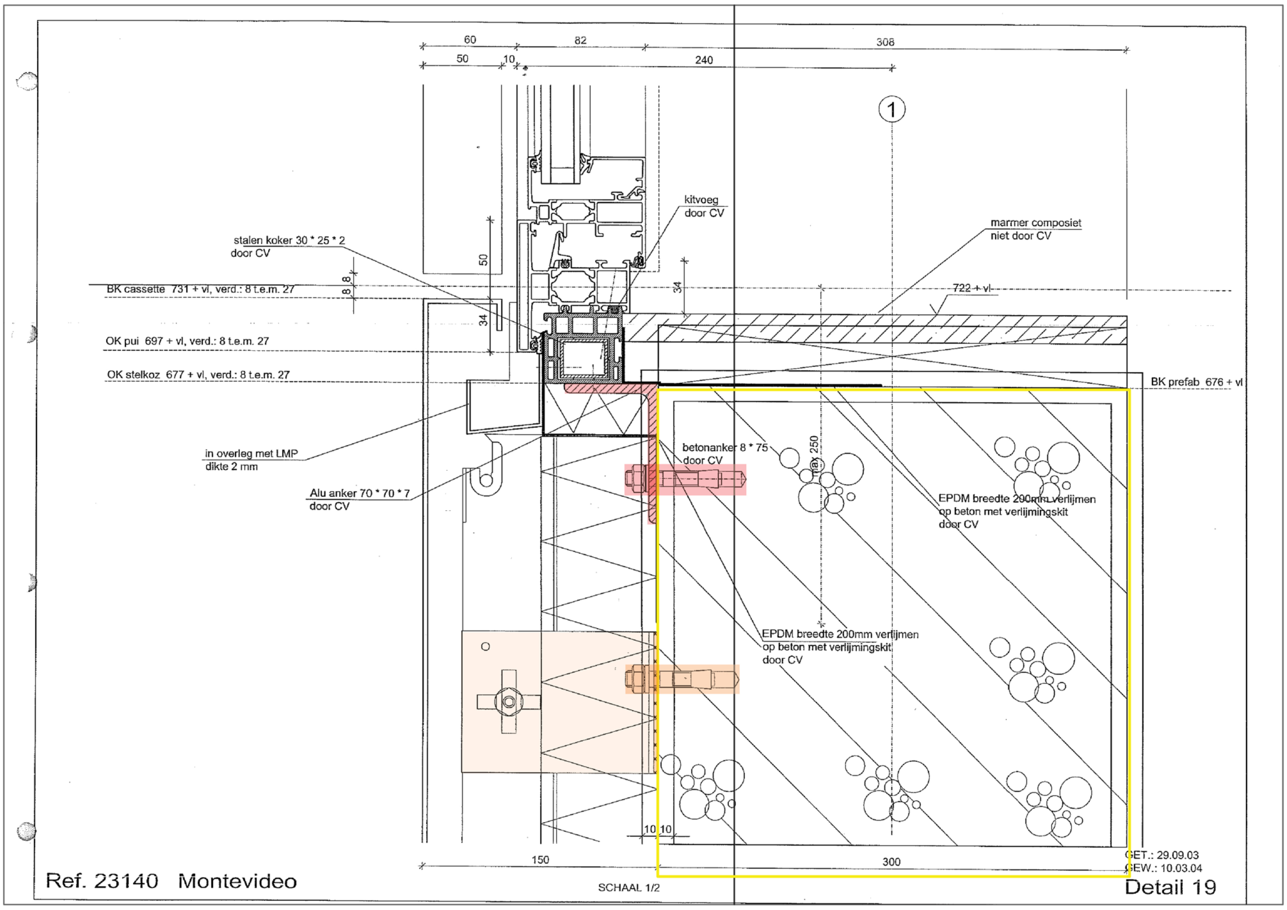



Figure 8.5 | Detail drawing of the lower part of the facade of the Montevideo with the light grey cassettes. Light blue: Yellow: the prefab concrete slab. Orange: fixing system of the cassettes to the slab. Red: fixing system of the window frame to the cassette | Source: Mecanoo, Municipal Archives Rotterdam

## 8.2 Scenario

In this paragraph is described what the objective is for this Case study and how it is derived from the analysis of the building. Based on this the design criteria and requirements are compiled.

### 8.2.1 Problem statement of the existing building

***Air quality***
The air quality in the area only just meets the minimum requirements of the WHO.

***Noise***
The facades of the building are exposed to a lot of ambient noise from traffic and industry. The minimum requirement for sound reduction is just met and there is no margin for sound absorption.

***Sustainability***
Many materials in the facade are made from materials that are poorly degradable and have high production costs.

### 8.2.2 Objective

Renovate the part of the façade, with the light grey cassettes, with a facade system that supports natural ventilation through the façade according to ventilation type C and filters particulate matter and NO2 out of the air.

### 8.2.3 Design criteria

***Healthy, natural ventilation***
The facade must have vents for natural ventilation. The following requirements apply:

- The air must be filtered for particulate matter and nitrogen dioxide
- Ambient noise must be absorbed

***Installation and maintenance***
The façade system must be able to be built on the existing façade structure, while the building remains habitable at all times.
To keep maintenance costs low, it is important that the maintenance effort and frequency of the system remain low.

***Sustainability***
To increase the sustainability of the building, it is important to reuse as many existing materials as possible.

## 8.3 Concept selection

For this Case Study, the concept of *Outside filter box: variant II* is selected. The priorities on which this choice is based and the explanation of the choice are presented below. See table 8.A for the overview of the priorities and the criteria.

### 8.3.1 Priorities

- The *acoustic damping* is a priority because it follows from the problem definition that this is only just sufficient in the current facade.
- Because this case is a *renovation* project, the concept must be *suitable* for this.
- It is a high building, which can only be reached from the outside with a Building Maintance Unit. Therefore, the concept must score high on the properties related to *maintance*.

### 8.3.2 Selection

For the acoustic damping it seems a logic choice to choose one of the filter box concepts. The Inside filter box, is not a good choice, however, since it's not suitable for a renovation project. Regarding the maintenance the outside filter boxes are almost similar, but variant II scores slightly better.

| | Hard criteria | | Air treatment | | | Design qualities | | Constructability | | Maintenance | | Total score: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dimensions | Pressure drop | Filter quality $NO_2$ | Filter quality PM | Thermal comfort | ▼ Acoustic damping | Design flexibility | ▼ Suitability for renovation project | Building speed on site | ▼ Maintenance effort | ▼ Maintenance frequency | |
| CYCLONE SEPARATOR with PCO | 🟢 | 🟠 | 2 | 1 | 1 | 1 | 2 | 3 | 3 | 2 | 3 | 18 |
| BIOFACADE Living Wall System | 🟢 | 🟢 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 14 |
| BIOFACADE Active Green Wall | 🟢 | 🟠 | 3 | 2 | 3 | 2 | 2 | 1 | 1 | 2 | 1 | 17 |
| Outside filter box: variant I | 🟢 | 🟢 | 2 | 2 | 2 | 3 | 2 | 3 | 3 | 1 | 2 | 20 |
| ▶ Outside filter box: variant II | 🟢 | 🟢 | 2 | 2 | 2 | 3 | 2 | 3 | 3 | 2 | 2 | 21 |
| Inside filter box | 🟢 | 🟢 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 3 | 2 | 20 |

Table 8.A | Quality table where the priorities and the selected concept are marked with arrows | Source: own work

## 8.4 Design plan

How the design parameters of the concept can be further elaborated on the existing facade of the case is shown in table 8.B.
For each design parameter this table indicates with what purpose it should be further elaborated and according to which method this was done.

| | Design parameter | Objective | Method |
|---|---|---|---|
| **Box** | Material | Suitable for application of PCO | Literature research |
| | Surface roughness | Optimize for PCO performance | Literature research |
| | Dimensions | Fit in existing façade structure | Analyzing building, drawing |
| | Shape | Fit in existing façade structure. | Considering the filter roll |
| | Color | Similar to existing color, matches with other façade elements | Analyzing building, literature research |
| | Mechanism to open box | Fast and easy to operate, watertight when closed | Analyzing references, drawing, making prototype |
| **PCO** | Coating or embedded in material | Work with low light intensity | Literature research |
| **Fibrous filter** | Performance | As high as possible withing the limit of max pressure drop | References |
| | Pressure drop | < 20 Pa | References |
| | Material | Durable, fire safe | Literature research, references |
| | Maintenance frequency | Not more than once per year | Calculation |
| | Thickness filter roll | As thin as possible to reduce the size of the roll | References |
| | Mechanism to change filter fabric | Easy to use | Analyzing references, drawing, making prototype |
| **Fixing system** | Attachment of box to underlying façade structure | Use existing fixing system as much as possible | Analyzing references, drawing |
| **Ventilation openings** | Frontside panel | Catches as much wind as possible,<br>No water leakage | Analyzing wind conditions and references, making prototype |
| | Into the room | Create good air circulation, proper size ventilation opening | Literature research, calculation |
| **Acoustics** | Measures to dampen noise | As small as possible | Analyzing references and literature |

Table 8.B | Table with the *design parameters* of the concept *'Outside filter box variant II'* and with what *objective* they should be worked out further and with what *method* that is achieved | Source: own work

## 8.5 Design development

This section shows how the chosen concept was developed in this study according to the goals and methods described in the Design plan in the previous section.

### 8.5.1 Box

***Material***
The literature review revealed several materials that are suitable for use with PCO. Two of the most obvious materials of these are polymer and metal. These are materials that can be easily made into a box and can serve as hosts for the catalyst TiO2.
Since the ventilation grille that is used in the design is aluminium. the rest of the box is designed as aluminium as well.

***Surface roughness***
For the PCO coating, a lot of contact surface means more performance. By applying a ventilation grille a whimsical surface is automatically created and a lot of contact surface is created.

***Dimensions***
The goal is to integrate the new panel into the current facade structure. The new panel will have the width of an existing panel, as shown in figure 8.6. This gives the new panel a width of 850 mm and a height of 1280 mm.
The thickness of the box is largely determined by the thickness of the filter roll. Taking into account space around it, the total thickness will be about 300 mm. This means that the box will be offset from the existing facade panels.

Figure 8.6 | Close-up of the facade. The dotted line indicates the panel that is replaced by the new panel | Source: (Mecanoo 2021)

***Shape***
The shape of the panel is largely determined by the thickness of the filter roll. Also, the ventilation grille needs to fit into the front end. To fit the shape into the rest of the facade, a rectangular shape is chosen.

***Color***
The desired color is light gray. The use of a TiO2 coating automatically results in a white color. It should be investigated how the TiO2 coating can be mixed with a color to obtain light gray. The advantage here is that the colors are already close together.

***Mechanism to open box***
The top of the box can be unclipped. When this is done, the ventilation grille can be unclipped from the box. This click system reduces the maintenance effort.

### 8.5.2 PCO

On a cloudless, sunny day, the south facade captures around 120,000 Lux and the facades in the shade around 20,000 Lux. So the facades in the shade capture around 17x less sunlight. This difference is smaller when it is an overcast day and when there is relatively more diffuse light.
When designing the appropriate PCO coating, a variant should be chosen where the light intensity has a lesser effect on the performance of the PCO, such as for example *'Hyphobic coating with silica'*, as explained in section 3.1.3.

### 8.5.3 Fibrous filter

As an example, a G4 filter is elaborated, as also discussed in Section 3.5 'Fibrous filter'. This type of filter was also tested in this research with the test setup as mentioned in chapter 6.
This filter seems to be a suitable choice because among the fibrous filters it has a low pressure drop.
The relevant properties of this filter are listed in table 8.C.

| | |
|---|---|
| Performance | Own test: 36% PM10, 30% PM2.5 and 21% PM1.0<br>According to website: 60% PM10 or larger |
| Pressure drop | 42 (20 mm thickness)<br>About 10 (5mm thickness) |
| Material | Polyester |
| Dust holding capacity | 460 $g/m^2$ (20 mm thickness)<br>About 100 (5mm thickness) |
| Thickness | 5 – 20 mm |

Table 8.C | Relevant properties of the G4-filter | Source: (wtw-filtershop, 2021)

***Performance***
The performance according to wtw-filtershop (2021) is 60% for PM10 or larger. This results in a score of 1 in the quality table. For a better score a better filter should be chosen. For this study nevertheless this filter will be used, because it is available.

***Pressure drop***
The pressure drop is well below the maximum value, when the filter cloth is maximum 5 mm thick.

***Material***
The material of this filter cloth is polyester. This is a durable material, but has to be made fireproof by impregna-

tion.

***Maintenance frequency***
In this example a ventilation flow of 0.0009 * 30 * 3600 = 97.2 $m^3$/ h is assumed. This is based on a room with a floor area of 30 $m^2$ and a minimum ventilation flow rate of 0.9 $dm^3$/s per $m^2$.

Assuming the filter has a thickness of 5 mm, a surface of 1 x 0.8 m and a dust holding capacity of 100 g/$m^2$ the dust holding capacity for this filter becomes:

$$\tau(h) = \frac{H * A}{0.01 * E * C * F}$$

with:
τ = dust holding capacity [g/$m^2$]
A = Surface of filter [$m^2$]
E = Efficiency [%]
C = Density of air pollution [g/$m^3$]
F = Volumetric flow rate [$m^3$/h]

Gives:

$$\tau(h) = \frac{100 * 1\ x\ 0.8}{0.01 * 60 * 20\ x\ 10^{-6} * 100}$$

$$\tau(h) = 11111\ hours$$

$$\tau(h) = \frac{11111}{8760} = 1.27\ years$$

Rounded down, therefore, this filter would have to be unrolled *annually*, so that a new part of the filter emerges.

***Thickness filter roll***
According to Sybke (2006), the thickness of the roll of filter material can be calculated using the following formula:

$$r_{buiten} = \sqrt{(\frac{l * d}{\pi} + r_{binnen}^2)}$$

with:
$r_{buiten}$ = radius outside of roller [mm]
$r_{binnen}$ = radius inside roller [mm]
l = Filter cloth length [mm]
d = thickness of filter cloth [mm]

If this filter has to last at least 10 years, the length of the filter roll must be at least 10 meters. Annually, 1 meter of new roll is then rolled out. The maximum diameter of the filter roll is:

$$r_{buiten} = \sqrt{(\frac{10{,}000 * 3}{\pi} + 20_{binnen}^2)}$$

$$r_{buiten} = 98\ [mm]$$

The diameter of the roll is then 2 * 98 = 196 mm, which can be rounded to 200 mm.

***Mechanism to change filter fabric***
The filter fabric is unwound annually using a string attached to the top and bottom rods around which the roll is wrapped. This is on the same principle how a roller blind can be rolled out, the difference being that here there are two rods and the roll is rolled from one rod to the other.

To change a filter roll a similar system can be used as that of changing a roll of paper in a printer, as shown in figure 8.7. This is a quick and easy way to keep the maintenance effort low.

Figure 8.7 | Photo which shows changing a roll of paper in a printer | Source: (HP, 2021)

## 8.5.4 Fixing system
The existing fixing system can be used. The old panels can be unscrewed and the new panels can be attached to the free corner profiles.
This is an advantage, because in this way no new fixing systems have to be installed and the existing insulation layer remains undamaged.

## 8.5.5 Ventilation openings

***Frontside panel***
A ventilation grille was chosen as the opening on the front side of the panel, as also examined in Section 4.3.5. . The acoustic damping can be incorporated immediately and does not have to be placed in the box itself. In this way, space can be saved and the box does not have to be that large.
The grille is supplied prefabricated and can be attached in its entirety to the front of the box.
With this panel an acoustic damping of 6 dB can be achieved.
See figure 8.8 for a photo of such a grille.

Figure 8.8 | Photo of a ventilation grille with acoustic absorbent material integrated, from manufacturer Duco under the name 'DucoGrille Acoustic G75'. | Source: (DUCO, 2021)

***Into the room***

Two options are available for creating a vent in the current facade:

1. Install a ventilation grille in the window frame
2. Drilling holes in the prefab concrete slab and sealing them with a ventilation grid.

Because in this design the renovation should be as easy and cheap as possible, option 2 was chosen. For option 1 each window frame including glass would have to be replaced, while for option 2 the entire window frame including glass can remain in place. In addition, the concrete element does not have a primary function for the load-bearing capacity of the building and it can be structurally justified to make cut-outs in it.

Then, by placing two tubes in these holes and connecting them to two holes in the back of the box, the air in the room can be connected to the air in the box. This is illustrated in figure 8.9.

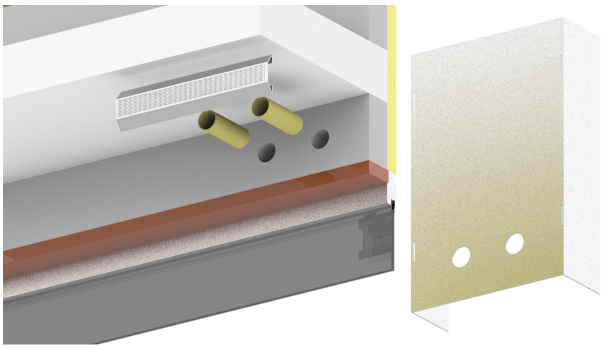


Figure 8.9 | Render of an exploded view with the ventilation grille, the ventilation tubes and the outside box | Source: own work

### 8.5.6 Acoustic measures

Acoustic dampening material is incorporated into the ventilation grille in the front of the panel. According to the manufacturer, this grille provides acoustic attenuation of approximately 6 dB.

## 8.6 Result

The result of the design development is presented in table 8.D. Every parameter is now defined in more detail.

In the next paragraph this is worked out in the design drawings, figures 8.10 till 8.19.

| | Design parameter | Result |
|---|---|---|
| **Box properties** | PCO friendly materials | Aluminium with painting that contains TiO2 |
| | Surface roughness | Use the roughness of the ventilation grille |
| | Dimensions | Shape is based on existing façade panels: 850 x 1280 mm |
| | Shape | Shape is rectangular |
| | Color | Same color as existing panels |
| | Mechanism to open box | Click-system for top lid and front ventilation grille panel |
| **Filter properties** | Performance | Own test:<br>Literature: 60% PM10 or larger |
| | Thickness | 5 mm |
| | Material | Polyester |
| | Mechanism to change filter fabric | Unwind filter roll to change visible filter fabric.<br>Click-system for roll itself. |
| **Fixing system** | Attachment of box to underlying façade structure | Fixed to existing fixing system |
| **Ventilation openings** | Front panel | Standard aluminium ventilation grille applied with integrated acoustic damping: 'DucoGrille Acoustic G75' |
| | Back panel | Two tubes through the existing prefab façade element that connect the air inside the box with the air inside the room |
| **Thermal comfort** | Measures to cool air | Optional: HDPE cylinder package with parrafin 17-Carbons fill |
| | Measures to preheat air | Optional: heating system inside ventilation grille inside the room |
| **Acoustics** | Measures to dampen noise | Acoustic dampening material is placed in the ventilation grille in the front and can reduce sound by 6 dB |

Table 8.D | How the design parameters are worked out | Source: own work

## 8.7 Design drawings

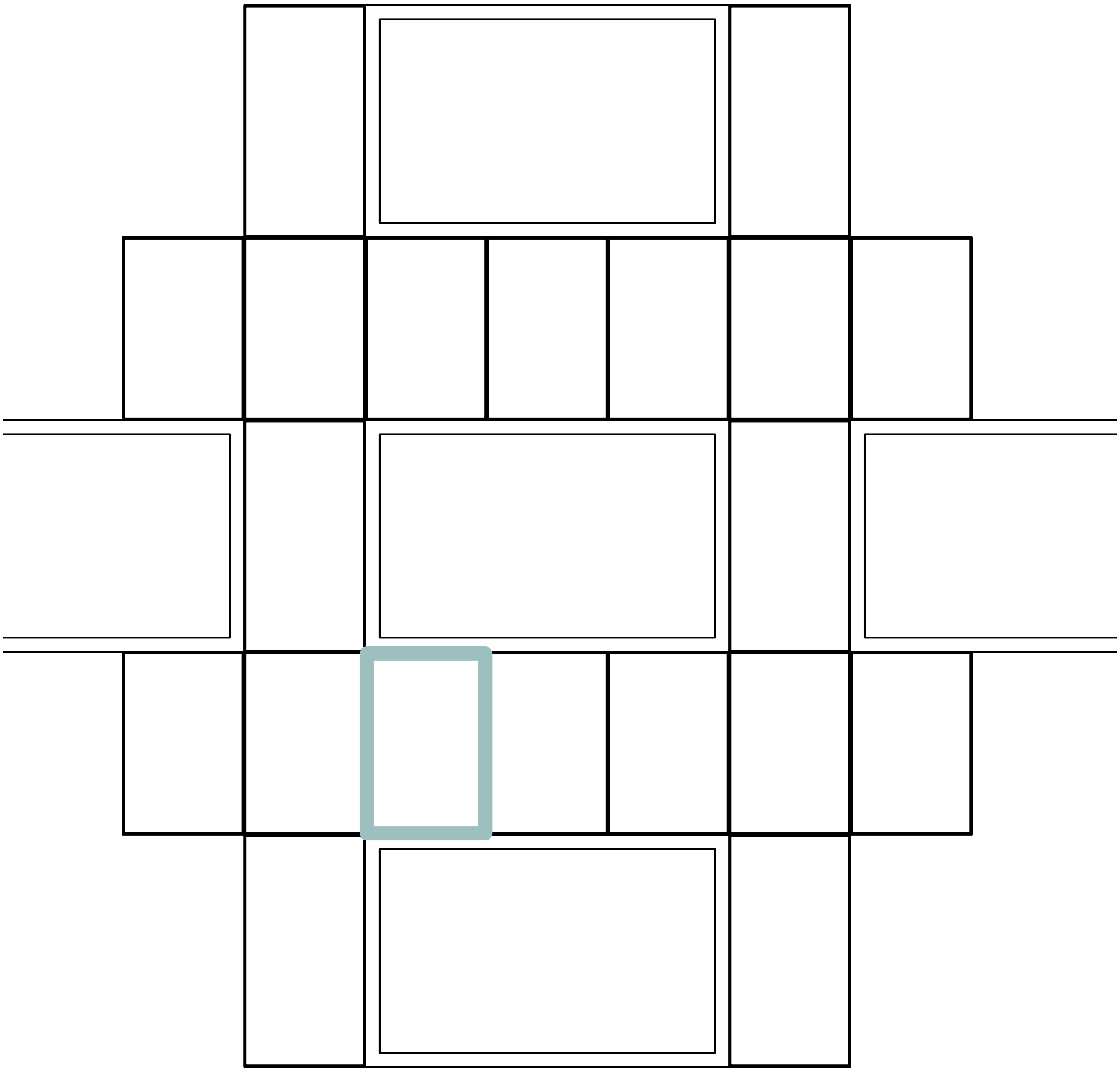


Figure 8.10 | 1:50 Front view of the existing facade with highlighted in blue the facade panel which is being replaced with the new facade panel | Source: Own work

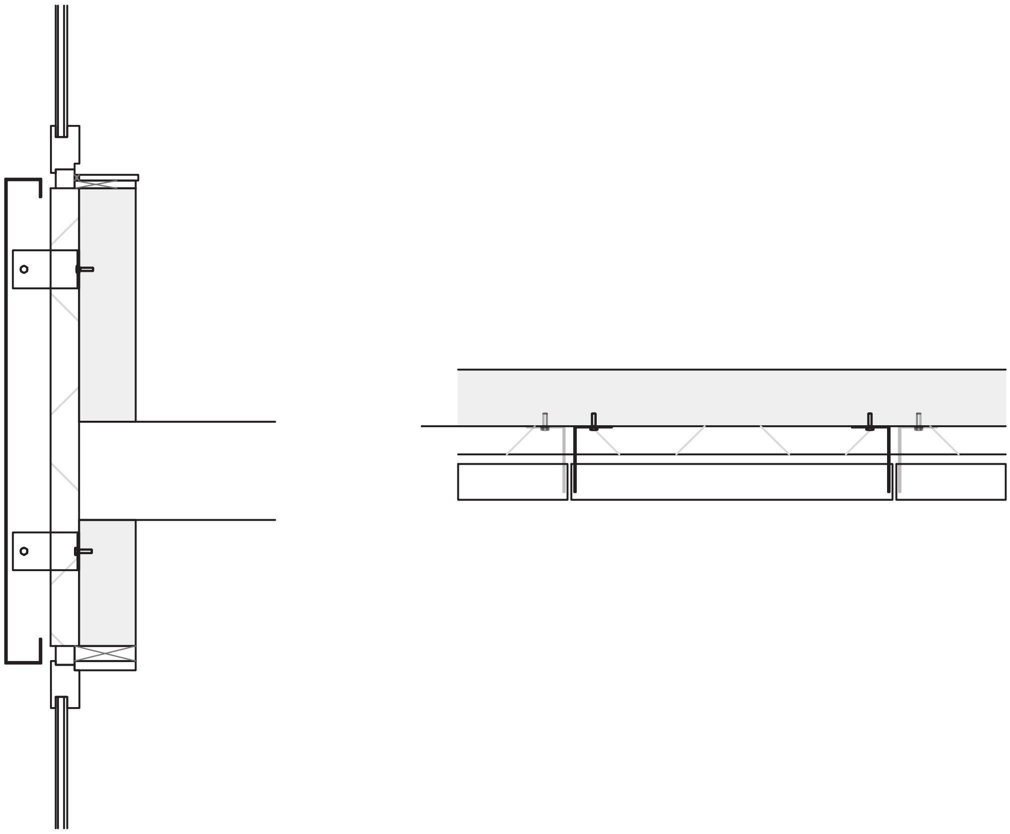


Figure 8.11 | 1:20 Section and top view of the *existing facade panel*. | Source: Own work

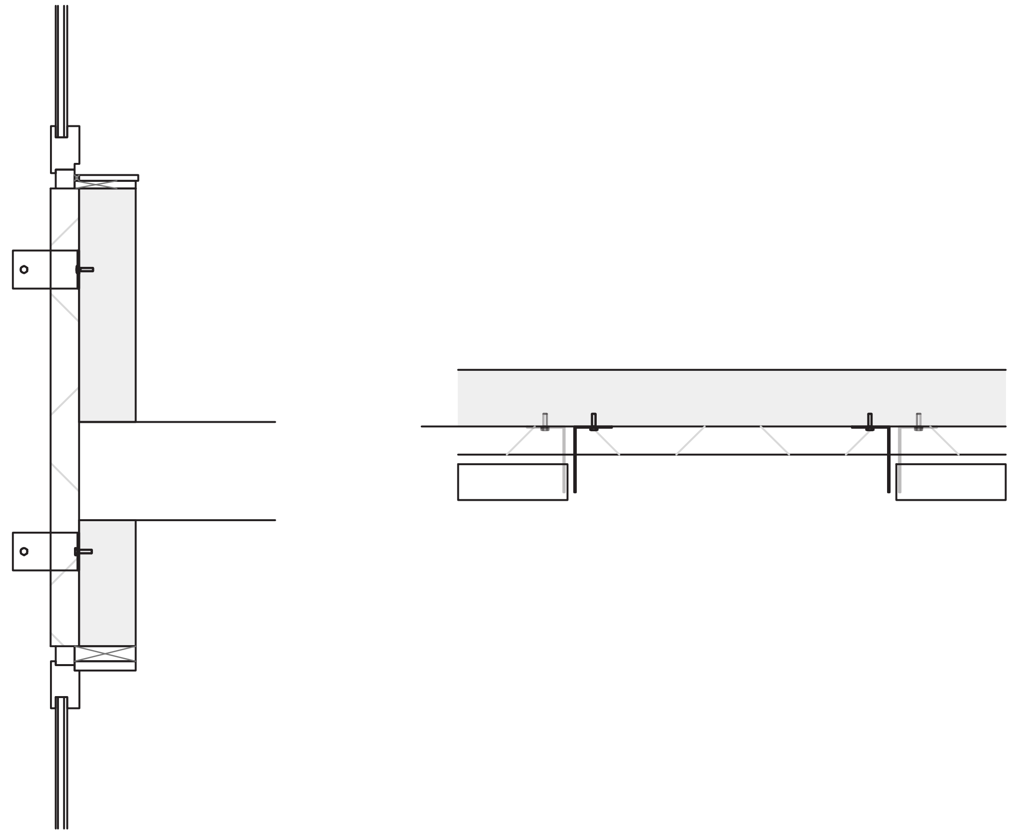


Figure 8.12 | 1:20 Section and top view of when the *existing facade panel* is removed. | Source: Own work

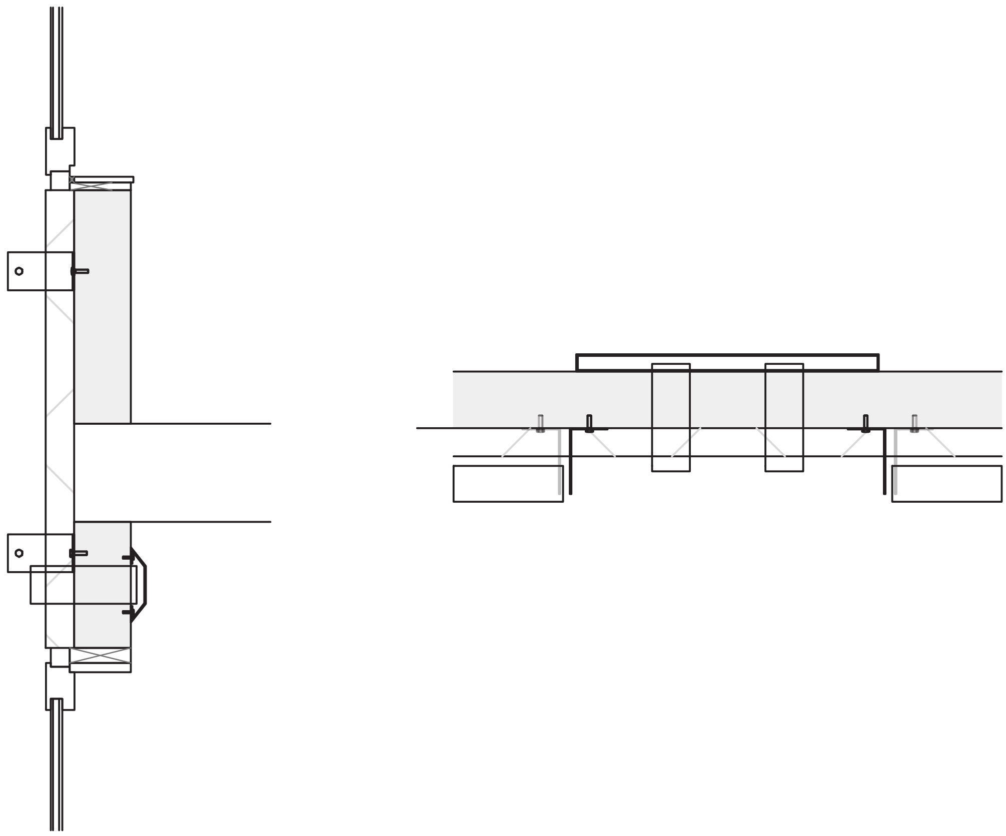


Figure 8.13 | 1:20 Section and top view with the *ventilation tubes*. | Source: Own work

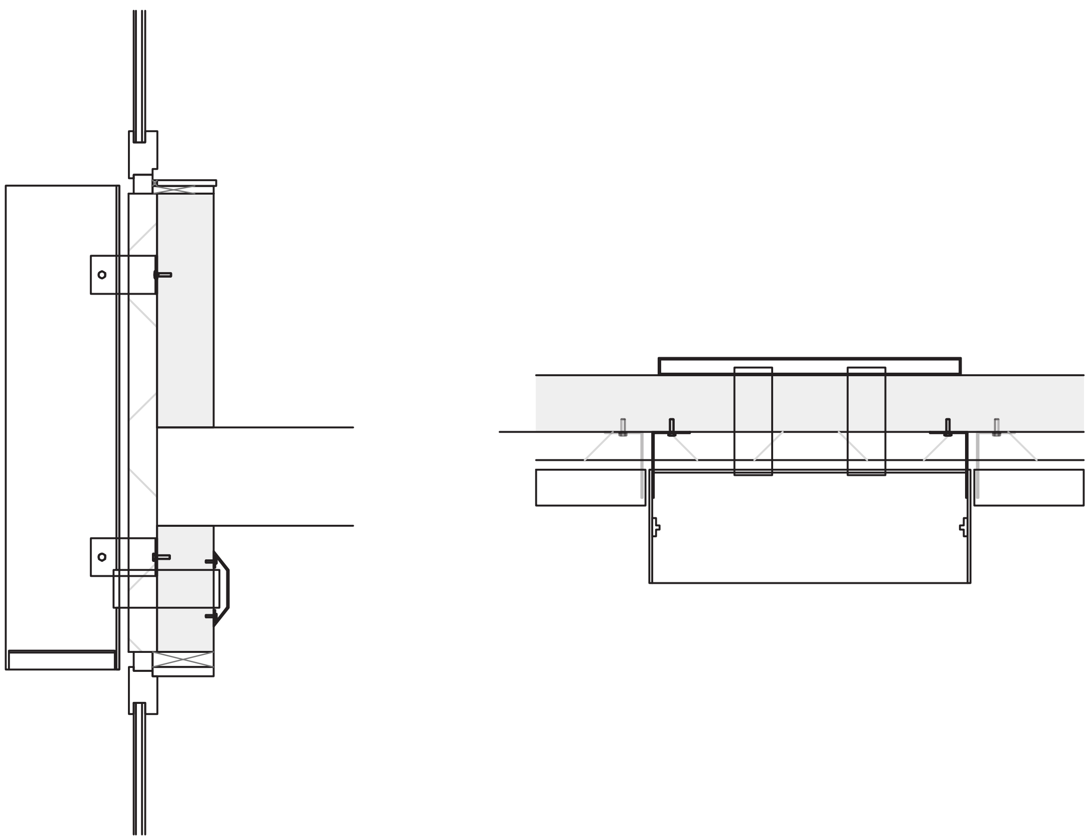


Figure 8.14 | 1:20 Section and top view with added the *aluminium casing* | Source: Own work

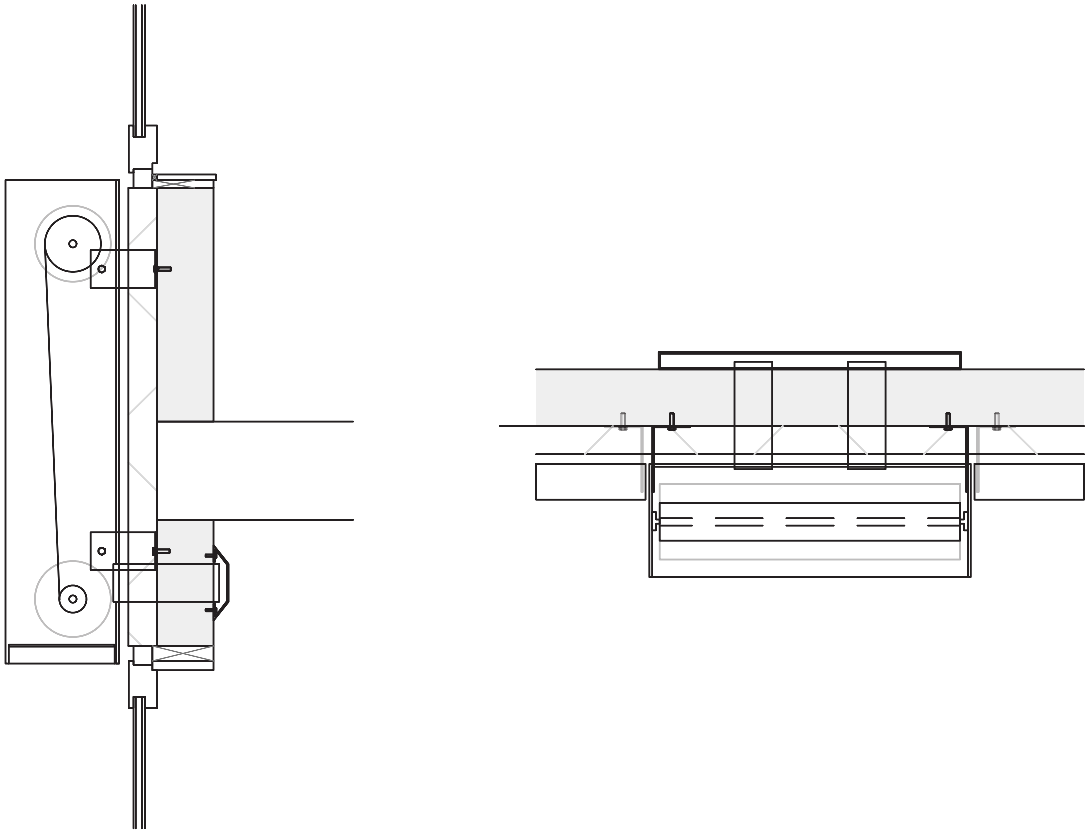


Figure 8.15 | 1:20 Section and top view with added the *filter roll* | Source: Own work

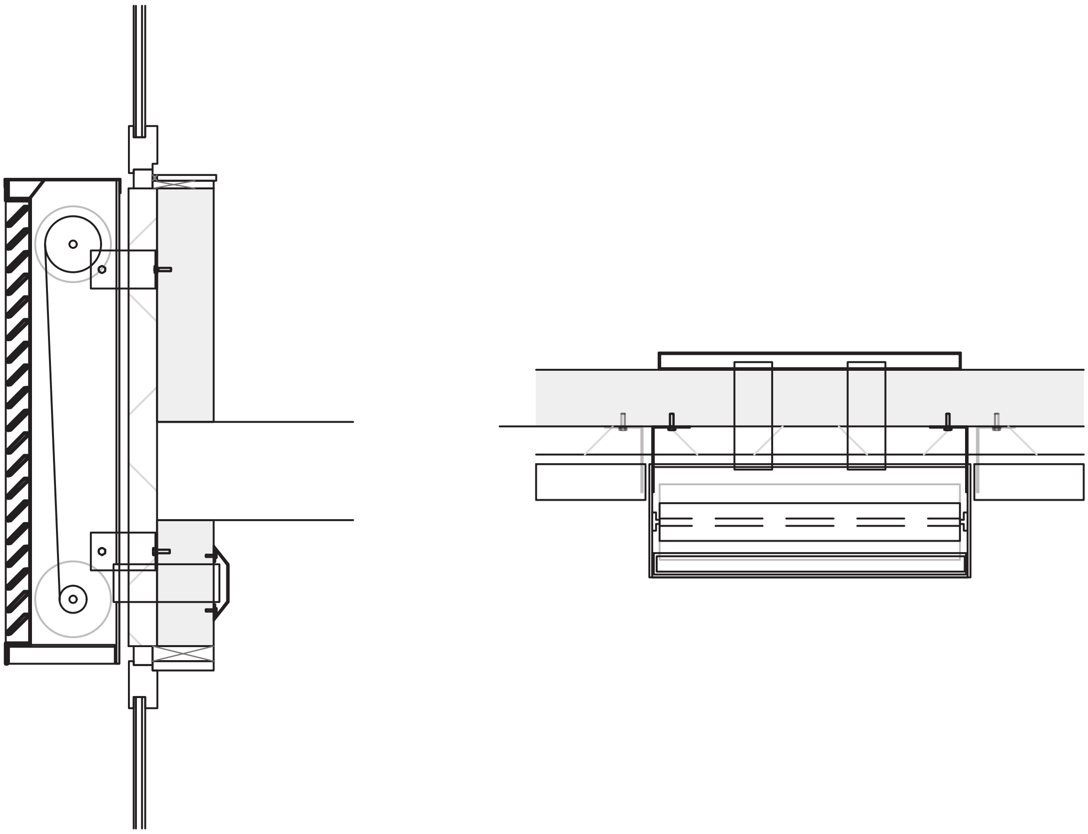


Figure 8.16 | 1:20 Section and top view with added the *ventilation grille* and the *top lid* | Source: Own work

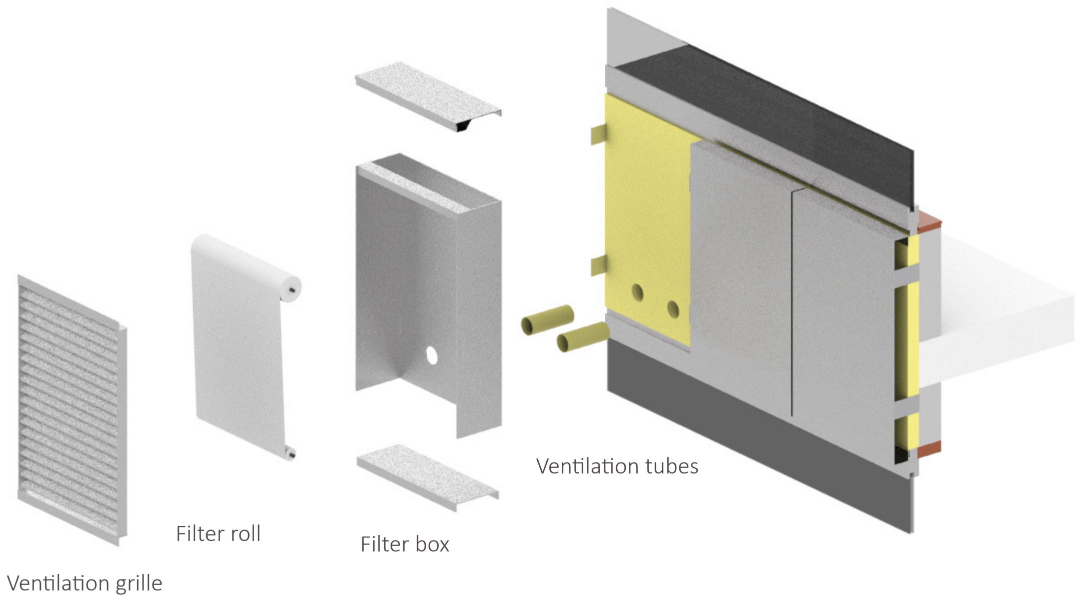



Figure 8.17 | Exploded view of the concept 'Outside filter box: variant II' worked out in Case study I | Source: Own work

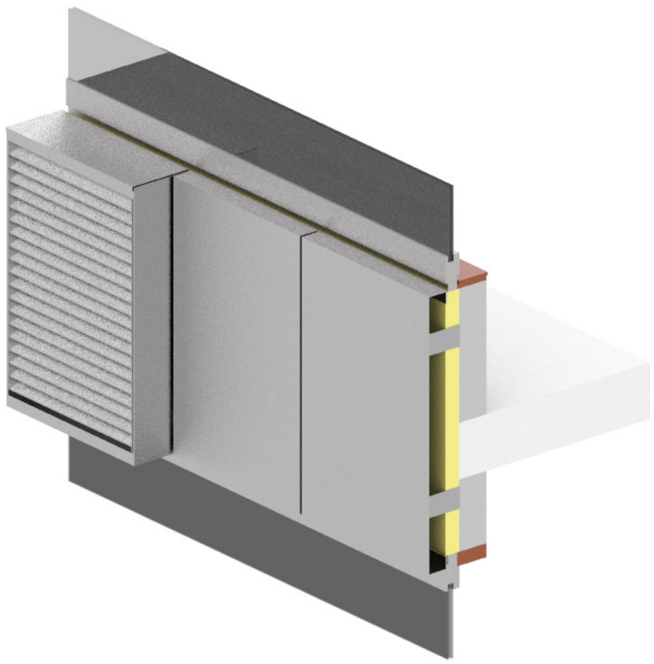


Figure 8.18 | Frontview 3D impression of the concept 'Outside filter box: variant II' worked out in Case study I | Source: Own work

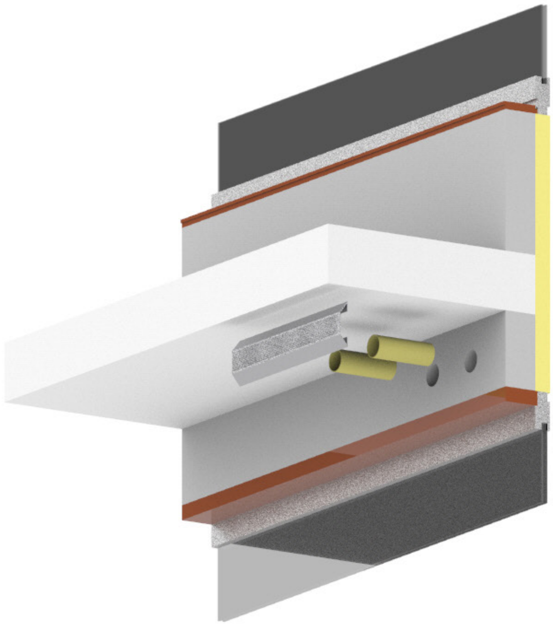


Figure 8.19 | Exploded view of the concept ‘Outside filter box: variant II’ worked out in Case study I viewed from the inside | Source: Own work

# 9

# Case Study II: New design for the Montevideo

This chapter presents the second Case study of the Montevideo in Rotterdam, which assumes a completely new and alternative design for a part of the facade. In this Case study, the concept of the 'Active Green Wall' was further developed.

The research question for this Case study is:
*How can the concept 'Active Green Wall' be developed further when a new design for a part of the facade of the Montevideo in Rotterdam is considered?*

- ***9.1 The Case***
This paragraph provides a brief introduction to the building and the specific facade that is being focused on

- ***9.2 Scenario***
The problem statement, objective, design criteria and design requirements of this case are presented in this paragraph

- ***9.3 Concept selection***
This paragraph presents which concept from Chapter 8 is selected for this Case

- ***9.4 Design plan***
For every design parameter of the concept a goal is determined and a method is presented to achieve this goal

- ***9.5 Design development***
How the concept is worked out according to the goals in the design plan is presented in this paragraph

- ***9.6 Design drawings***
The end result of the Case Study in the form of drawings

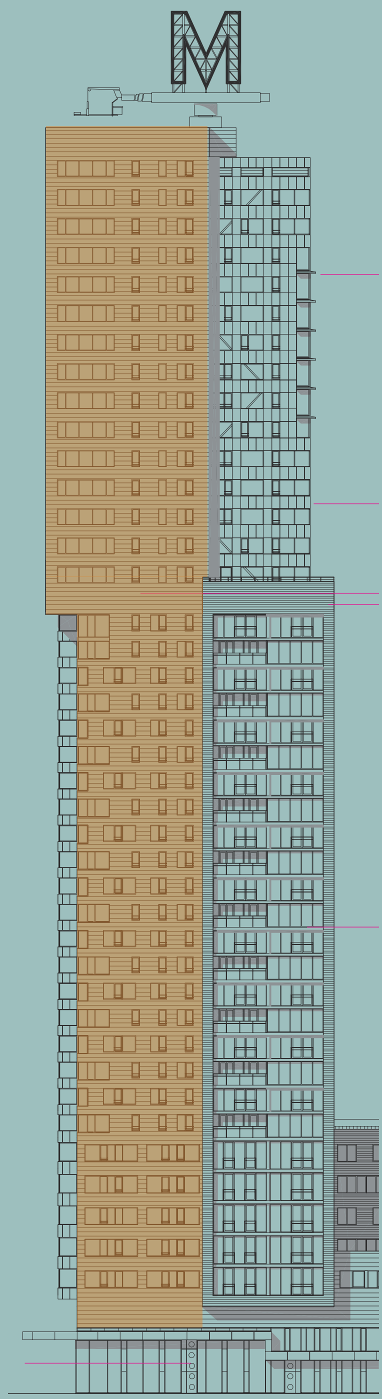


Figure 9.1 | South east front view of the Montevideo with highlighted in orange the facade that is focused on in this Case study | Source: Mecanoo, Municipal Archives Rotterdam

## 9.1 The case

For this Case Study, the same building was used as the Case Study in Chapter 9. Basic information about the building can be found in Section 9.1.

### 9.1.1 The facade

The facade focused on in this Case Study is the facade with the mixed orange coloured brickwork , as shown in the photo in figure 9.2.
The detail drawing of this facade is presented in figure 9.3 on the next page, which serve as the basis for developing a new design for the facade.

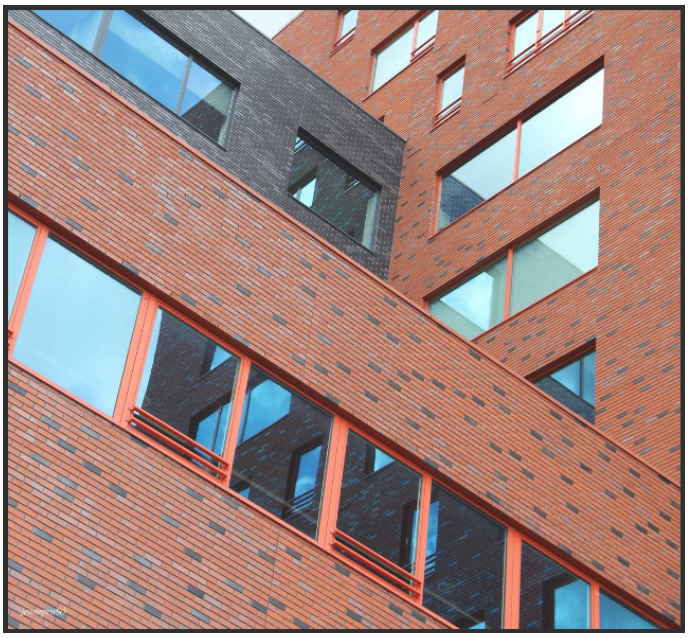


Figure 9.2 | Close-up of the part of the facade of the Montevideo with the mixed orange coloured brickwork | Source: (Pen, 2012)

## 9.2 Scenario

In this paragraph is described what the objective is for this Case study and how it is derived from the analysis of the building. Based on this the design criteria and requirements are compiled.

### 9.2.2 Objective

Make an alternative design for the for the building with the same look on the outside that supports natural ventilation through the façade according to ventilation type C and filter particulate matter and NO2 out of the air.

### 9.2.3 Design criteria

***Maintenance***
Because the facade is only accessible from the outside with a Building Maintenance Unit, it is important that either the maintenance frequency is low or the panel can be maintained from the inside.

***Design flexibility***
The appearance of the facade on the outside should remain the same. On the inside, however, the facade must offer a high degree of design flexibility for the occupants.

***Filter performance***
For this case we are looking for a system with a high filter performance.

***Thermal comfort***
As energy prices rise, it is important that air can be pre-heated in winter and cooled in summer in a sustainable way.

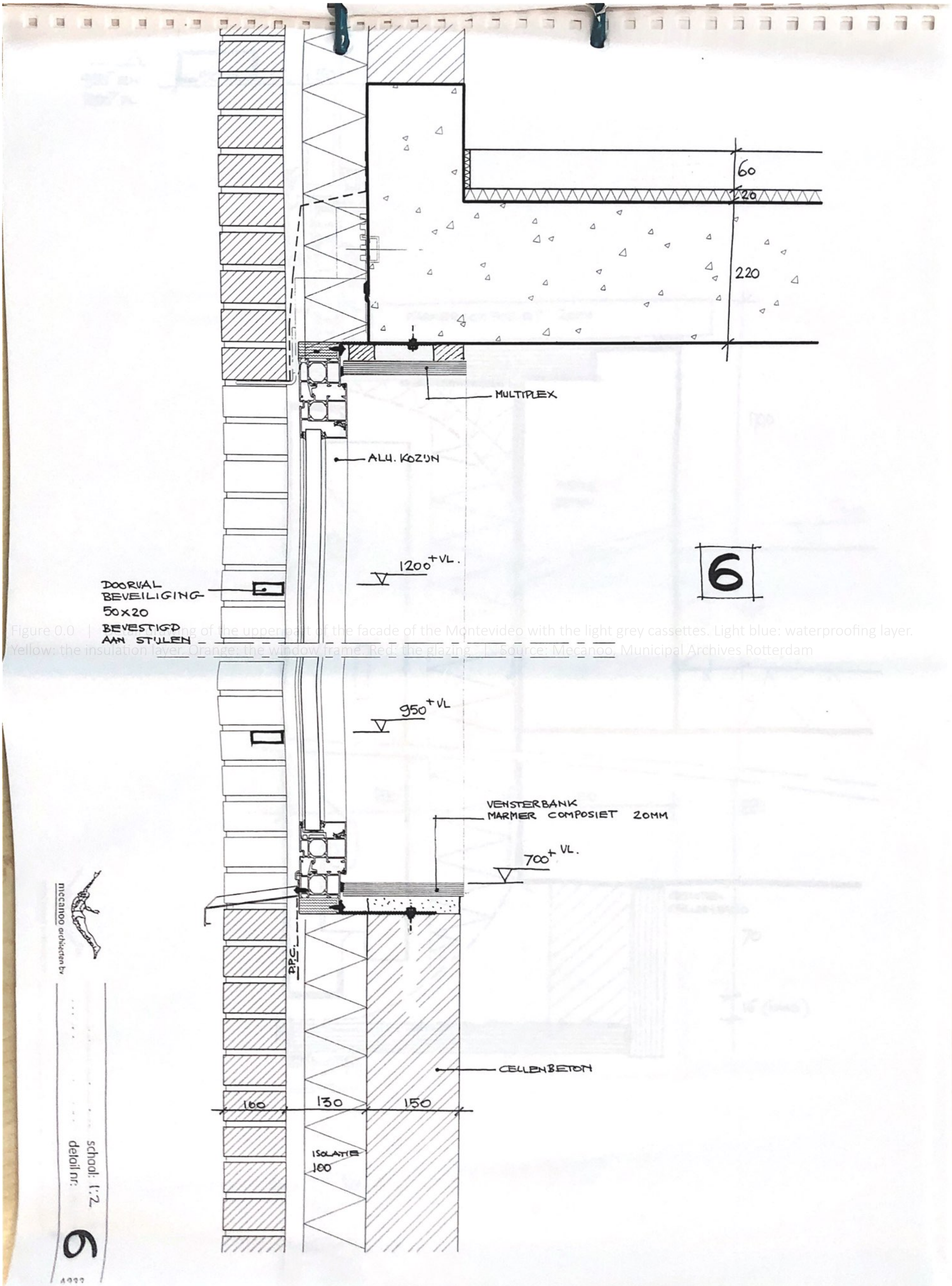



Figure 9.3 | Detail drawing of the part of the facade of the Montevideo with the mixed orange colored brickwork | Source: Mecanoo, Municipal Archives Rotterdam

## 9.3 Concept selection

For this Case Study, the concept of "Active Green Wall" is chosen. The priorities on which this choice is based and the explanation of the choice are presented below. See table 9.A for the overview of the priorities and the criteria.

### 9.3.1 Priorities

- Since this system is being designed for a resi dence room, it is important that the filtering effect is good.
- The thermal comfort must be improved, because the cooling load and heating load must be kept low.
- The facade must be maintenance friendly, be cause maintenance from outside is only possible with a BMU.

### 9.3.2 Selection

- The air treatment of this concept scores well for each criterion. The thermal comfort of the incoming air can be improved by planting, be cause plants have a cooling effect on the air flowing by.
- The filter quality of this concept scores well for both particulate matter and nitrogen dioxide.
- The maintenance effort of this concept is aver age, because it is easily accessible from the inside, but the maintenance of the plants re quires time and knowledge.

| | Hard criteria | | Air treatment | | | Design qualities | | Construct-ability | | Mainte-nance | | Total score: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dimensions | Pressure drop | ▶ Filter quality $NO_2$ | ▶ Filter quality PM | ▶ Thermal comfort | Acoustic damping | Design flexibility | ▶ Suitability for renovation project | Building speed on site | Maintenance effort | Maintenance frequency | |
| CYCLONE SEPARATOR with PCO | 🟢 | 🟡 | 2 | 1 | 1 | 1 | 2 | 3 | 3 | 2 | 3 | 18 |
| BIOFACADE Living Wall System | 🟢 | 🟢 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 14 |
| ▶ BIOFACADE Active Green Wall | 🟢 | 🟡 | 3 | 2 | 3 | 2 | 2 | 1 | 1 | 2 | 1 | 17 |
| Outside filter box: variant I | 🟢 | 🟢 | 2 | 2 | 2 | 3 | 2 | 3 | 3 | 1 | 2 | 20 |
| Outside filter box: variant II | 🟢 | 🟢 | 2 | 2 | 2 | 3 | 2 | 3 | 3 | 2 | 2 | 21 |
| Inside filter box | 🟢 | 🟢 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 3 | 2 | 20 |

Table 9.A | Quality table where the priorities and the selected concept are marked with arrows | Source: own work

## 9.4 Design plan

How the design parameters of the concept can be further elaborated on the existing facade of the case is shown in table 9.B.
For each design parameter this table indicates with what purpose it should be further elaborated and according to which method this was done.

| | Design parameter | Objective | Method |
|---|---|---|---|
| **Ventilation opening** | Type | aesthetically integrated in exterior of the surrounding façade | Literature study References |
| | Material | Similar to surrounding façade | Analyzing reference drawings |
| **Insulation layer** | Thickness | Same as surrounding façade | Analyzing reference drawings |
| | Material | Same as surrounding façade | Analyzing reference drawings |
| | Configuration of holes | Minimum needed for desired flow rate | Calculation |
| **'Living Wall System'** | Geometry | Must connect to prefab concrete slabs, not too thick, must fit in existing façade structure | Analyzing reference drawings |
| | Material | Sustainable | Literature study |
| **Vegetation** | Species | Root structure must be below max pressure drop | Literature study |

Table 9.B | Table with the *design parameters* of the concept *'Active Green Wall'* and with what *objective* they should be worked out further and with what *method* that is achieved | Source: own work

## 9.5 Design development

### 9.5.1 Ventilation opening

***Type***
To integrate the ventilation openings within the brickwork a so called *'Mashrabiya'* is used. This is a typical Middle Eastern type of wall opening, where holes between the bricks are created by placing the bricks at a distance to each other and leave out the mortar between the bricks. See figure 9.4 for a sketch that presents this idea.

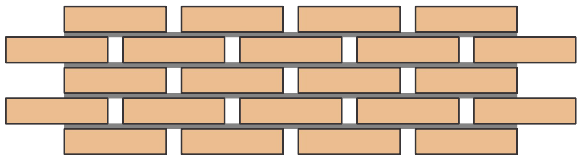


Figure 9.4 | Drawing of a so-called 'Mashrabiya', a type of masonry where ventilation holes are created between the bricks | Source: own work

***Material***
The same masonry as the surrounding façade is used, which is the mixed orange coloured brickwork as on the photo in paragraph 10.1.

### 9.5.2 Insulation layer

***Thickness***
The thickness of the insulation layer is determined by the thickness of the insulation layer that is designed for the

surrounding construction, which is 100 mm.

***Material***
The material of this insulation is a resol rigid foam from the manufacturer ‘Kingspan’.

***Configuration of holes***
The total area of the required ventilation opening is calculated using the following formula:

$$A_{opening} = \frac{Ventilatiedebiet\ [\frac{m^3}{s}]}{V_{max}\ [\frac{m}{s}]}$$

Where $V_{max}$ is the maximum air velocity of the air coming out of the opening. This is determined by the Building Code to prevent drafts and is given as 0.2 m/s.

The ventilation flow rate is also given by the Building Regulations and is 0.0009 $m^3$/s per m2 of floor area. Assuming an average floor area of 30 m2 this is: 0.0009 * 30 = 0.027 $m^3$/s in total.

Entering these values into the formula gives:

$$A_{opening} = \frac{0.027\ [\frac{m^3}{s}]}{0.2\ [\frac{m}{s}]}$$

$$A_{opening} = 0.135\ m^2$$

Which is 135000 mm2.

When a circular hole with a diameter of 100 mm is assumed this means that the amount of holes that are needed in the insulation layer is:

$$Amount\ of\ holes = \frac{A_{opening}}{\pi * r^2}$$

$$Amount\ of\ holes = \frac{135000}{\pi * 50^2}$$

$$Amount\ of\ holes = 17.2$$

Which is about 17 holes with a diameter of 100 mm, rounded down.

### 9.5.3 'Living Wall System'

***Geometry***
The geometry of the panel is determined by the facade structure, which gives a size of about 1700 x 1250 mm. See figure 9.5 for the location where the facade panel is located.

Figure 9.5 | Front view of the facade as designed by Mecanoo. The light blue boxes indicate the locations where the new design is located | Source: own work

***Material***
The frame can be made from steel.
The substrate can made from different materials, depending on which plants are placed. In the example of a 'Living Wall System' as presented by Pérez-Urrestarazu et al. (2016) a textile fabric is used which consists of one layer of polyamide and one layer of polypropylene.

***Vegetation***
Different plants can be selected for the use in a LWS. In the research of Pettit et al. (2017) different examples are presented and tested.
The *Nematanthus glabra* is a species which has a root structure that causes the lowest pressure drop of about 24 Pa.

The result of the design development is presented in figures 9.6 till 9.8

## 9.6 Design drawings

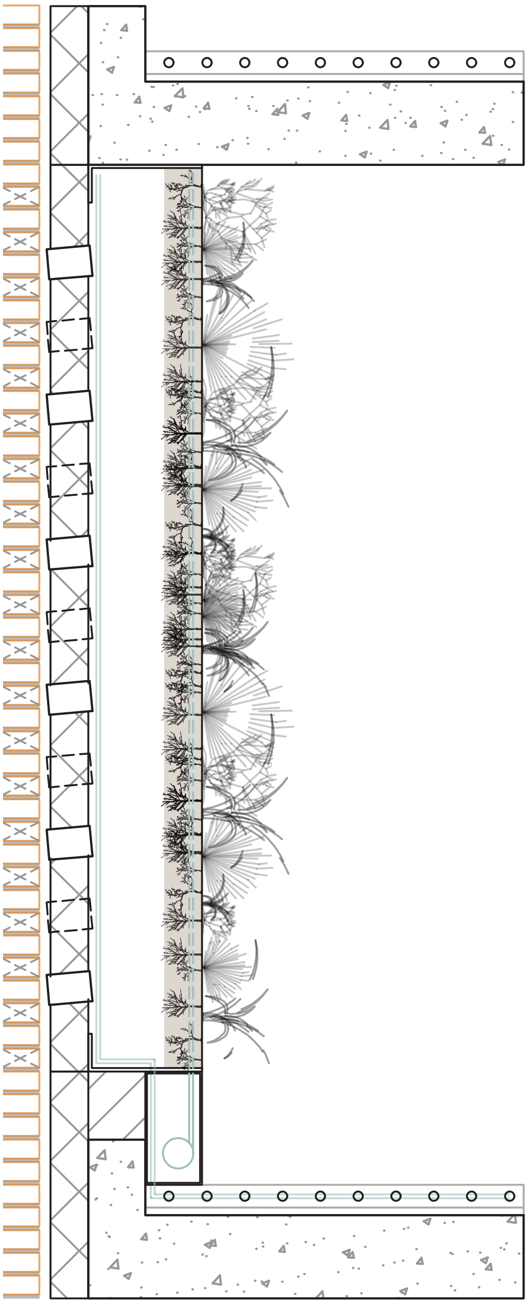


Figure 9.6 | Section AA' | Source: Own work

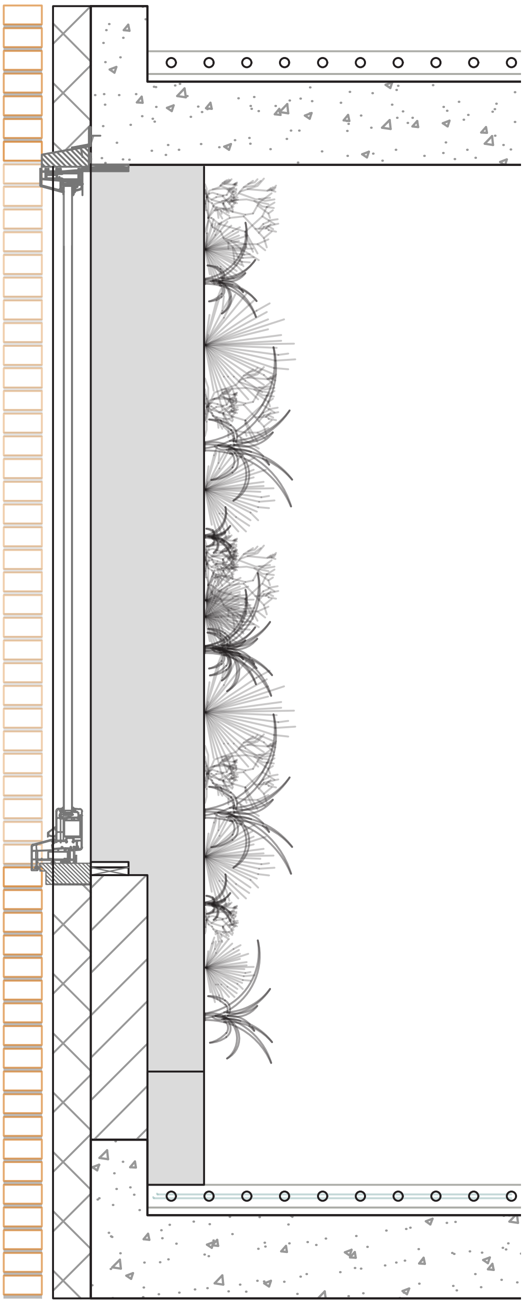


Figure 9.8 | Section BB' | Source: Own work

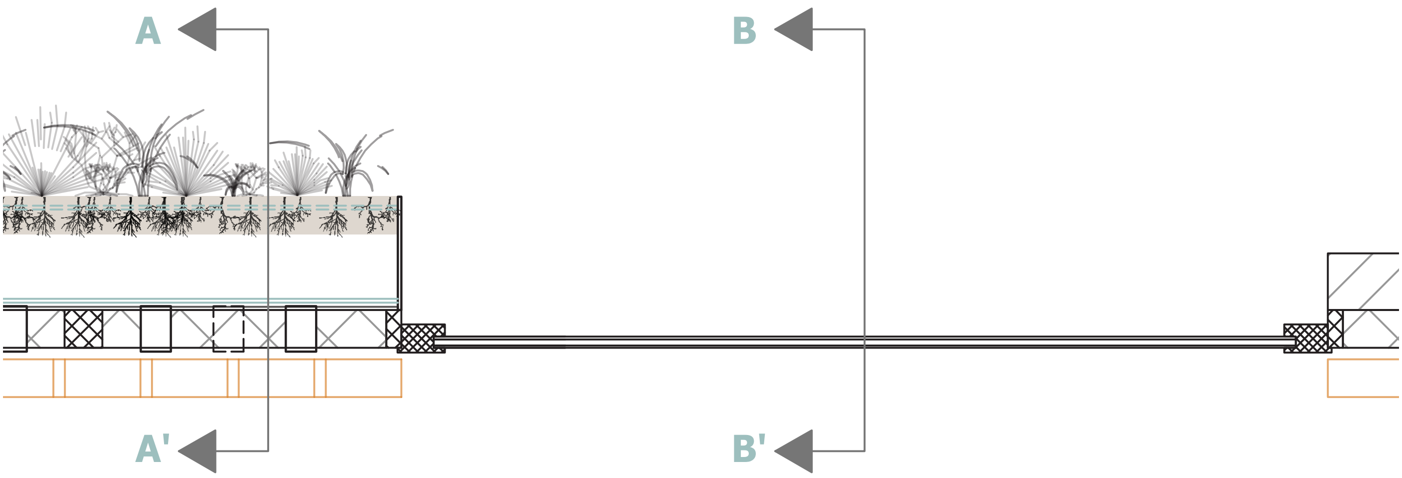



Figure 9.7 | Top view of concept 'Active Living Wall' further worked out in Case study II | Source: Own work

# 10
# Conclusion

## Main question

Today, ambient air pollution is still a major problem and a risk to human health and the environment. The starting point of this research is to solve the problem in the building industry and with the use of natural ventilation. The purpose of this research is to add a new function to the facade by filtering the incoming air using existing air purification technologies and applying them in an innovative way in the facade. Therefore, the main question of this research is as follows:

***How can the façade of a high-rise building in an industrialized region be designed to improve the indoor air quality when ventilation type C is used?***

Several sub-questions form a basis on which the main question can be answered.

## Literature review

***Which air purification technologies form the basis of this research?***
The air purification technologies that form the basis of this study were selected on the basis of whether they filter the right pollutant and whether the technologies could be applied in a facade for practical reasons.

Technologies for which references could easily be found in the built environment formed obvious reasons for selection, such as the *Living Wall System,* the *Active Green Wall* and *Fibrous filters*.
Less common technologies were also selected, such as the *Cyclone separator* and *Photocatalytic oxidation (PCO)*.

***How can the different technologies be compared to each other?***
The technologies were evaluated according to three criteria, the *filter quality of $NO_2$ and PM* and the *maintenance frequency.*

For filtering $NO_2$ *PCO* and the *Active Green Wall (AGW)* are the obvious choices, where the AGW is also a good choice for filtering particulate matter. The most obvious choice for filtering particulate matter seems to be the electret filter.
Most of the technologies need at least yearly maintenance, but PCO and the cyclone separator don't need maintenance at all during lifetime when designed properly

***Which ventilation openings are relevant for this research?***
In this study, existing ventilation openings were examined, outlined and compared. These include the following five: *operable window, operable vent, ventilation grille, wall ventilation* and the *mashrabiya.*

***How do the different ventilation openings relate to each other?***
To compare the ventilation openings they are evaluated according to three criteria: *air circulation, thermal comfort* and *acoustical properties*.

The analysis showed that the *operable vent* by itself is the best choice in terms of air circulation, especially in cold climates where this type is placed at the top of window frames.
In terms of thermal comfort, the *double facade* and the *operable vent* are the best choices.
The acoustical sound attenuating measures can be well integrated in almost every ventilation opening except the *operable window* and the *mashrabiya*

This analysis shows that the operable vent and double facade generally score well and are therefore almost always a good choice. The Mashrabiya and operable window, on the other hand, are not good choices on their own. If one chooses one of these types, adjustments will have to be made to the design of the ventilation opening or the construction supporting it.

## Validation

***Is it possible to test filters at home for their performance and pressure drop?***

The set-up is easy to make at home with relatively few supplies. Most of the equipment is relatively cheaply available and can be purchased for use at home.
As far as safety is concerned, the fact that open flames must be used, smoke is generated and the air is unhealthy must be taken into account. In a bathroom, safety can certainly be ensured.

To a certain extent the results can be used to say something about the *performance* of the filter objects. The accuracy of the PM meter was good enough for this. However, the tests are not reliable enough to determine an absolute value for the performance of the filter, because the air flow was difficult to predict and therefore it was often difficult to perform a correct measurement. However, it did prove possible to compare different filters and variants.

The anemometer was not accurate enough for the low wind speeds in the tube. It was therefore not possible to determine the *pressure drop* at low wind speeds. For this a lab setup with a pressure gauge is better. Only for high wind speeds an estimate of the pressure drop has been made.

***How can the test results support the design?***
The most important question that can be answered is if, under the conditions of the test, the air flows through the filter material at all. If this is measured with the anemometer or determined by hand, it can be stated that the material is suitable for use in a system with a natural air flow. In this way the test can support the design somewhat by determining whether the air flows through the material or not.

By comparing different variants, a preference can be expressed to prefer one particular variant over another when designing a concept, when looking at the results of the performance of the tests.

## Boundary conditions

***What are the hard criteria that the concept designs must meet?***
Het concept ontwerp moet voldoen aan een maximale pressure drop van 20 Pa en moet gemaakt kunnen worden met afmetingen die in een gevel passen en het liefst in de standaard maten.

***What are the soft criteria with which the concepts can be compared to each other?***
Het belangrijkste onderdeel is hoe het concept de binnenkomende lucht op een positieve manier kan beïnvloeden. Dit gebeurt allereerst door de filter quality te bapelen, waarmee iets kan worden gezegd over de performance van het concept bij een bepaalde pressure drop. De thermal comfort en air circulation zeggen iets over de kwaliteit van de lucht als het gaat om een comfortabele manier van ventileren.

De design qualities zijn opgesteld om te bepalen hoe goed een systeem het geluid kan dempen van buiten en hoeveel invloed de gebruiker heeft op het ontwerp.

Wat betreft de constructability wordt gekeken naar hoe goed het concept in een renovatie project kan worden toegepast en hoe snel het op locatie gebouwd kan worden.

Tot slot worden de concepten beoordeeld op hoeveel maintenance ze nodig hebben gedurende de lifespan en hoeveel moeite het onderhoud vervolgens kost.

## Concept design

***What concepts have been developed?***
A total of six concepts were created: the *cyclone separator with PCO, Living Wall System (LWS), Active Green Wall (AGW),* two types of *Outside filter boxes* and one *inside filter box*

***How did the different concepts develop?***
The concepts were made based on three main choices: the *air purification technologies, the ventilation principle* and *the construction type.* In total in this research six concepts have been developed.

When choosing the *air purification technologies*, it was considered which technologies can be combined well to filter both particulate matter and nitrogen dioxide. Some technologies complement each other so that they function even better together.
The *ventilation principle* was chosen based on whether a direct or indirect air flow is both achievable and preferable. The question of whether the air is brought into the room in a concentrated way or is distributed evenly across the facade also plays a role.
The choice of a *construction type* is mainly based on the extent to which a structure is integrated into the facade. If the structure runs through all the layers of the facade it is called an integral facade construction. When the construction is only placed on the outside of the facade as cladding then it is called an exterior facade panel.

***How do the different concepts relate to each other?***
The six concepts have been analyzed by giving them scores based on the hard an soft criteria.
In general, the scores of the different concepts are fairly close, especially for the three concepts with a *filter box*. *The Living Wall System* comes out worst in the analysis, mainly because the air treatment and maintenance are very weak.
The highest score is obtained by the Outside filter box: variant II, which is elaborated in Case study I.

## Answering the main question

An answer to the main question was given by six concept designs and two further elaborations in two case studies of the building 'Montevideo' in Rotterdam, in the Netherlands.
The concept designs and case studies were made to serve as inspiration for designers interested in developing air filtering facade systems. The designs in this research are mainly a conceptual example and are not yet a product. This research provides a theoretical basis for coming up with further concepts and applying them in other case studies. The recommendations outline how the case study designs could be further developed into a product design.

# Recommendations

A view recommendations are presented concerning the air purification technologies and further developing the concept design into product design.

## Air purification technologies

Two air purification technologies that were discovered during the literature review have not been further examined, despite the fact that they do meet the criteria of this study and can therefore be part of the answer to the main question.
It concerns the following technologies: inertial impaction filter and dynamic insulation

### *Inertial impaction filter*

In the research of Zhang et al. (2018), a filter is presented that mainly uses the capture mechanism "inertial impaction". It consists of a panel with small pores in which the air flow is changed from its direction causing the particulate matter to fly straight ahead and collide with a collection box. Figure R.1 shows this in a drawing, indicating the trajectory of the air and the particle.
This technology is said to be efficient at a low pressure drop.

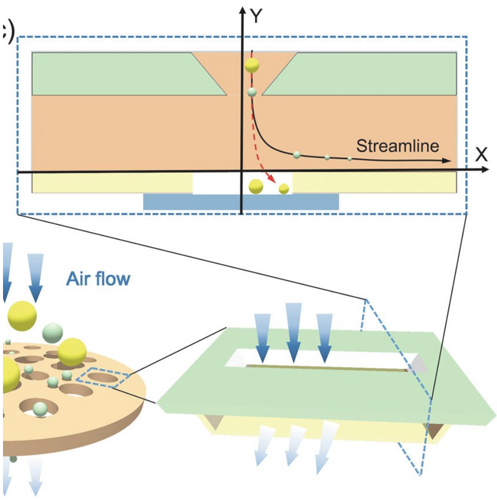



Figure R.1 | Conceptual image of the 'inertial impaction filter' | Source: (Zhang et al., 2018) (Imbabi, 2006)

### *Dynamic insulation*

In the research of Imbabi (2006) an example is given of a so-called 'Modular breathing panel'. Here air is led through a construction, after which it goes through the insulation material and where this insulation material also functions as a filter, see figure R.2 for a schematic representation. The great advantage here is that the outside air, as it flows through the insulation material, slowly changes to the inside temperature. The air thus requires less or no preheating or cooling. This technology is therefore ideally suited for a system where thermal comfort is important.

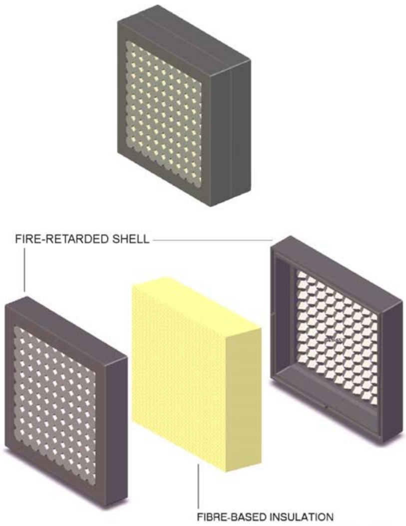



Figure R.2 | Conceptual image of the 'inertial impaction filter' | Source: (Imbabi, 2006)

## Product design

To turn the designs in the Case studies into a product design, more factors will need to be considered. These include structural safety, Rc value and more as shown in table R.A.

| | |
|---|---|
| Structural safety | ● Fixing system present. Common construction.<br>● Fixing system present. Unusual construction.<br>● No fixing system present. Unusual construction. |
| Drainage | ● Watertight separation structure between inside and outside present<br>● It is not certain whether the structure is completely watertight<br>● No watertight separation structure between inside and outside present |
| Fire safety | ● A1, A2 / no risk for spread<br>● B / possibility of spread<br>● C, D, E, F / high risk of spread |
| Lifetime | ● >> 10 years<br>● circa 10 years<br>● < 10 years |
| Rc-value | ● > 3,5 $\frac{m^2 * K}{W}$, no thermal bridges<br>● < 3,5 $\frac{m^2 * K}{W}$, thermal bridges |

Table R.A | Other hard criteria to define the concept design into a product design and the definition of the three color codes | Source: own work

***CFD analysis***

In order to be able to predict in detail how the air flows through a ventilation system, a simulation can be made with Computational Fluid Dynamics (CFD). An example of software for this is the program 'Ansys'. In this program an airflow with particulate matter can be simulated, with which the path that the particulate matter follows through the filter can be determined. By placing objects like a filter in the airflow and having the particles 'stick' to it, it is possible to simulate the performance of a filter system. Also the pressure drop of the airflow through the openings can be determined.
In figure R.3 an example is given of the result of a CFD simulation of a cyclone separator.

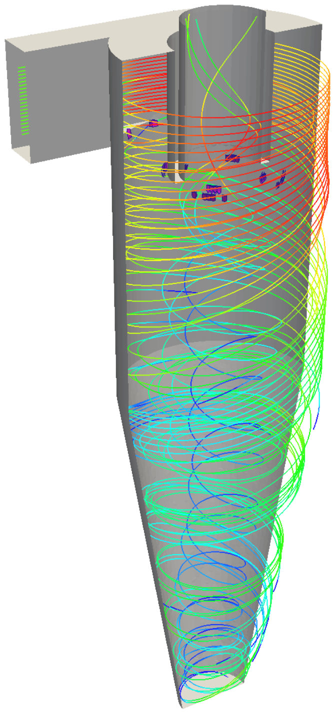


Figure R.3 | Illustration of a CFD analysis of air through a cyclone separator | Source: (CFD Direct, 2017)

# References


Ali Express. (2021). Titanium dioxide [Photo]. https://nl.aliexpress.com/item/32966928744.html

Bakalar, N. (2020, July 14). Air Pollution Takes a Global Toll on Heart Health. The New York Times. https://www.nytimes.com/2020/07/09/well/live/air-pollution-takes-a-global-toll-on-heart-health.html

Beerens, J., Snijders, A., & Bilow, M. (2019). A review for using green for air purification, heat stress reduction and energy saving. Delft University of Technology. http://resolver.tudelft.nl/uuid:a0170ff8-9ab3-465c-b042-ba1a052f5297

Biler, A., Unlu Tavil, A., Su, Y., & Khan, N. (2018). A Review of Performance Specifications and Studies of Trickle Vents. Buildings, 8(11), 152. https://doi.org/10.3390/buildings8110152

Bouwbesluit 2012. (2021, July 1). Bouwbesluit Online 2012. Retrieved September 14, 2021, from https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012

Brown, P., & Cox, C. L. (2017). Fibrous Filter Media. Elsevier Gezondheidszorg. https://www.sciencedirect.com/book/9780081005736/fibrous-filter-media#-book-description

Butler, P. (2020, January 27). Urban populations in south-east at greatest risk from air pollution. The Guardian. https://www.theguardian.com/environment/2020/jan/27/one-in-19-deaths-uk-cities-air-pollution

CFD Direct. (2017). OpenFOAM Barycentric Tracking [Illustration]. https://cfd.direct/openfoam/free-software/barycentric-tracking/

Chavhan, M. V., & Mukhopadhyay, A. (2015). Fibrous Filter to Protect Building Environments from Polluting Agents: A Review. Journal of The Institution of Engineers (India): Series E, 97(1), 63–73. https://doi.org/10.1007/s40034-015-0071-3

Christoforidou, C., Tenpierik, M. J., & Bergsma, A. C. (2019). Facade design for noise attenuation and thermal comfort through natural ventilation for high-rise office buildings in the Netherlands. Technical University of Delft. http://resolver.tudelft.nl/uuid:ba172faa-b7e2-4067-a51b-0bbea9a25e9e

Chun, D., Kim, M., Lee, J., & Ahn, S. (2008). TiO 2 coating on metal and polymer substrates by nano-particle deposition system (NPDS). CIRP Annals, 57(1), 551–554. https://doi.org/10.1016/j.cirp.2008.03.111

Damen, N. A. G. A., Brouwers, H. J. H., Lichtenberg, J. J. N., van de Wouw, P. M. F., & Eindhoven University of Technology. (2014, June).

De nieuwe groene gevel. https://research.tue.nl/nl/studentTheses/de-nieuwe-groene-gevel

designboom. (2012). brick pattern house by alireza mashhadimirza [Photo]. https://www.designboom.com/readers/brick-pattern-house-by-alireza-mashhadimirza/

DUCO. (2021). DUCO. https://www.duco.eu/nl/producten/raamventilatie

Ellis-Petersen, H. (2020, December 24). Pollution killed nearly 1.7m people in India in 2019 – study. The Guardian. https://www.theguardian.com/world/2020/dec/23/pollution-killed-nearly-17-million-people-in-india-in-2019-study

EPA. (2021, May 26). Particulate Matter (PM) basics [Illustration]. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics

Etacheri, V., di Valentin, C., Schneider, J., Bahnemann, D., & Pillai, S. C. (2015). Visible-light activation of TiO2 photocatalysts: Advances in theory and experiments. Journal of Photochemistry and Photobiology C: Photochemistry Reviews, 25, 1–29. https://doi.org/10.1016/j.jphotochemrev.2015.08.003

Etheridge, D. W., & Ford, B. (2008). Natural ventilation of tall buildings. CTBUH World Congress, Dubai. https://www.semanticscholar.org/paper/Title-%3A-Natural-Ventilation-of-Tall-Buildings-%E2%80%93-and-Etheridge-Ford/5d9a10b0fab58a0dcb3cca9d44f5e3d0a41f7725

Fenger, J. (1999). Urban air quality. Atmospheric Environment, 33(29), 4877–4900. https://doi.org/10.1016/s1352-2310(99)00290-3
Gas Encyclopedia. (2021). Nitrogen dioxide [Illustration]. https://encyclopedia.airliquide.com/nitrogen-dioxide

Hashimoto, K., Irie, H., & Fujishima, A. (2005). TiO2Photocatalysis: A Historical Overview and Future Prospects. Japanese Journal of Applied Physics, 44(12), 8269–8285. https://doi.org/10.1143/jjap.44.8269
Hofs, Y. (2020, April 27). De stikstofcrisis, bijna vergeten: miljarden lossen het conflict niet op. de Volkskrant. https://www.volkskrant.nl/nieuws-achtergrond/de-stikstofcrisis-bijna-vergeten-miljarden-lossen-het-conflict-niet-op~b97c66cb/?referrer=https%3A%2F%2Fwww.google.com%2F

HP. (2021). HP DesignJet printers [Photo]. https://www.hp.com/emea_middle_east-en/large-format-printers/designjet-printers/t930.html
Huang, S. H., Chen, C. W., Kuo, Y. M., Lai, C. Y., McKay, R., & Chen, C. C. (2013). Factors Affecting Filter Penetration and Quality Factor of Particulate Respirators. Aerosol and Air Quality Research, 13(1), 162–171. https://doi.org/10.4209/aaqr.2012.07.0179

Hystad, P., Larkin, A., Rangarajan, S., AlHabib, K. F., Avezum, L., Calik, K. B. T., Chifamba, J., Dans, A., Diaz, R., du Plessis, J. L., Gupta, R., Iqbal, R., Khatib, R., Kelishadi, R., Lanas, F., Liu, Z., Lopez-Jaramillo, P., Nair, S., Poirier, P., . . . Brauer, M. (2020). Associations of outdoor fine particulate air pollution and cardiovascular disease in 157 436 individuals from 21 high-income, middle-income, and low-income countries
(PURE): a prospective cohort study. The Lancet Planetary Health, 4(6), e235–e245. https://doi.org/10.1016/s2542-5196(20)30103-0

Hyun, O., Baek, M., Moon, J., & Ahn, Y. (2016). Performance evaluation of two-stage electrostatic air filter with low-ozone emission corona charger. Particulate Science and Technology, 35(1), 71–76. https://doi.org/10.1080/02726351.2015.1131788

Imbabi, M. S. E. (2006). Modular breathing panels for energy efficient, healthy building construction. Renewable Energy, 31(5), 729–738. https://doi.org/10.1016/j.renene.2005.08.009

Irga, P., Paull, N., Abdo, P., & Torpy, F. (2017). An assessment of the atmospheric particle removal efficiency of an in-room botanical biofilter system. Building and Environment, 115, 281–290. https://doi.org/10.1016/j.buildenv.2017.01.035

Ji, Z., Xiong, Z., Wu, X., Chen, H., & Wu, H. (2009). Experimental investigations on a cyclone separator performance at an extremely low particle concentration. Powder Technology, 191(3), 254–259. https://doi.org/10.1016/j.powtec.2008.10.015

Kadam, V. V. (2018). Multifunctional air filtration for respiratory protection using electrospun nanofibre membrane. RMIT University. https://www.researchgate.net/publication/329672584_Multifunctional_Air_Filtration_for_Respiratory_Protection_using_Electrospun_Nanofibre_Membrane

Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. Environmental Pollution, 151(2), 362–367. https://doi.org/10.1016/j.envpol.2007.06.012

Kang, I. S., Xi, J., & Hu, H. Y. (2018). Photolysis and photooxidation of typical gaseous VOCs by UV Irradiation: Removal performance and mechanisms. Frontiers of Environmental Science & Engineering, 12(3). https://doi.org/10.1007/s11783-018-1032-0

Karagoz, I., Avci, A., Surmen, A., & Sendogan, O. (2013). Design and performance evaluation of a new cyclone separator. Journal of Aerosol Science, 59, 57–64. https://doi.org/10.1016/j.jaerosci.2013.01.010

Knaack, U., Klein, T., Bilow, M., & Auer, T. (2007). Fassaden: Prinzipien der Konstruktion (German Edition) (1st ed.). Birkhäuser.

Lattanzio, L. (n.d.). Particulate Matter Sensing for Air Quality Measurements. Sensirion. Retrieved September 19, 2021, from https://www.sensirion.com/en/about-us/newsroom/sensirion-specialist-articles/particulate-matter-sensing-for-air-quality-measurements/

Liu, G., Xiao, M., Zhang, X., Gal, C., Chen, X., Liu, L., Pan, S., Wu, J., Tang, L., & Clements-Croome, D. (2017). A review of air filtration technologies for sustainable and healthy building ventilation. Sustainable Cities and Society, 32, 375–396. https://doi.org/10.1016/j.scs.2017.04.011

Luchtmeetnet. (2021). Luchtmeetnet. Retrieved September 14, 2021, from https://www.luchtmeetnet.nl/

Maggos, T., Bartzis, J., Leva, P., & Kotzias, D. (2007). Application of photocatalytic technology for NOx removal. Applied Physics A, 89(1), 81–84. https://doi.org/10.1007/s00339-007-4033-6

Meteoblue. (2021). Klimaat Rotterdam. Www.Meteoblue.Com. Retrieved October 30, 2021, from https://www.meteoblue.com/nl/weer/historyclimate/climatemodelled/rotterdam_nederland_2747891

Ottelé, M., Haas, E. M., & Technische Universiteit Delft. (2011, June). The Green Building Envelope. http://resolver.tudelft.nl/uuid:1e38e393-ca5c-45af-a4fe-31496195b88d

Ottelé, M., Ursem, W. J. N., Fraaij, A. L. A., & van Bohemen, H. D. (2011). The development of an ESEM based counting method for fine dust particles and a philosophy behind the background of particle adsorption on leaves. Air Pollution XIX. Published. https://doi.org/10.2495/air110201

Ottelé, M., van Bohemen, H. D., & Fraaij, A. L. (2010). Quantifying the deposition of particulate matter on climber vegetation on living walls. Ecological Engineering, 36(2), 154–162. https://doi.org/10.1016/j.ecoleng.2009.02.007
Pen, J. (2012). Montevideo Rotterdam [Photo]. https://zoom.nl/foto/architectuur/1835104/montevideo-rotterdam

Pérez-Urrestarazu, L., Fernández-Cañero, R., Franco, A., & Egea, G. (2016). Influence of an active living wall on indoor temperature and humidity conditions. Ecological Engineering, 90, 120–124. https://doi.org/10.1016/j.ecoleng.2016.01.050

Pettit, T., Irga, P., Abdo, P., & Torpy, F. (2017). Do the plants in functional green walls contribute to their ability to filter particulate matter? Building and Environment, 125, 299–307. https://doi.org/10.1016/j.buildenv.2017.09.004
Podgórski, A., Bałazy, A., & Gradoń, L. (2006). Application of nanofibers to improve the filtration efficiency of the most penetrating aerosol particles in fibrous filters. Chemical Engineering Science, 61(20), 6804–6815. https://doi.org/10.1016/j.ces.2006.07.022

Riley, W. J., McKone, T. E., Lai, A. C. K., & Nazaroff, W. W. (2002). Indoor Particulate Matter of Outdoor Origin: Importance of Size-Dependent Removal Mechanisms. Environmental Science & Technology, 36(2), 200–207. https://doi.org/10.1021/es010723y

Robatherm. (2021). De luchtfilternorm ISO 16890 [Illustration]. https://www.robatherm.com/nl/technologie/luchtfilternorm-ISO16890

Sakthivel, Y. (2019, June). Urban Facades (Thesis). TU Delft. http://resolver.tudelft.nl/uuid:51921425–4226-4848-8fff-54ee8e603908

Sensirion. (2021). Sensirion. Retrieved September 19, 2021, from https://www.sensirion.com/en/

Solution Pharmacy. (2021). Cyclone separator [Illustration]. https://solution-pharmacy.in/cyclone-separator/

Sybke. (2006, April 28). [Formula to calculate roll thickness] [Forumpost]. wetenschapsforum. https://www.wetenschapsforum.nl/viewtopic.php?t=28353

Timmers, V. R., & Achten, P. A. (2016). Non-exhaust PM emissions from electric vehicles. Atmospheric Environment, 134, 10–17. https://doi.org/10.1016/j.atmosenv.2016.03.017

Trudell, C. (2015). Breathe Brick [Illustration]. https://www.architectmagazine.com/awards/r-d-awards/citation-breathe-brick_o
van Turnhout, J., Hoeneveld, W. J., Adamse, J. W. C., & van Rossen, L. M. (1981). Electret Filters for High-Efficiency and High-Flow Air Cleaning. IEEE Transactions on Industry Applications, IA-17(2), 240–248. https://doi.org/10.1109/tia.1981.4503932

W. B. Faulkner, & B. W. Shaw. (2006). EFFICIENCY AND PRESSURE DROP OF CYCLONES ACROSS A RANGE OF INLET VELOCITIES. Applied Engineering in Agriculture, 22(1), 155–161. https://doi.org/10.13031/2013.20191
Wolfson, R. (2011). Energy, Environment, and Climate (Second ed.). W. W. Norton & Company.

World Health Organization. (2006). WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide : global update 2005 : summary of risk assessment. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiBv_rK2_7yAhURNuwKHVAVADgQFnoECAMQAQ&url=http%3A%2F%2Fwhqlibdoc.who.int%2Fhq%2F2006%2FWHO_SDE_PHE_OEH_06.02_eng.pdf&usg=AOvVaw0lMNPW1mWi-iJwOOS-gWqy
wtw-filtershop. (2021). wtw-filtershop. Retrieved September 14, 2021, from https://www.wtw-filtershop.nl/nl/

Xing, Y.-F., Xu, Y.-H., Shi, M.-H., & Lian, Y.-X. (2016). The Impact of PM2.5 on the Human Respiratory System. Journal of Thoracic Disease, 8(1), E69–E74. https://doi.org/10.3978/j.issn.2072-1439.2016.01.19

Yang, J. H., Han, Y. S., & Choy, J. H. (2006). TiO2 thin-films on polymer substrates and their photocatalytic activity. Thin Solid Films, 495(1–2), 266–271. https://doi.org/10.1016/j.tsf.2005.08.195

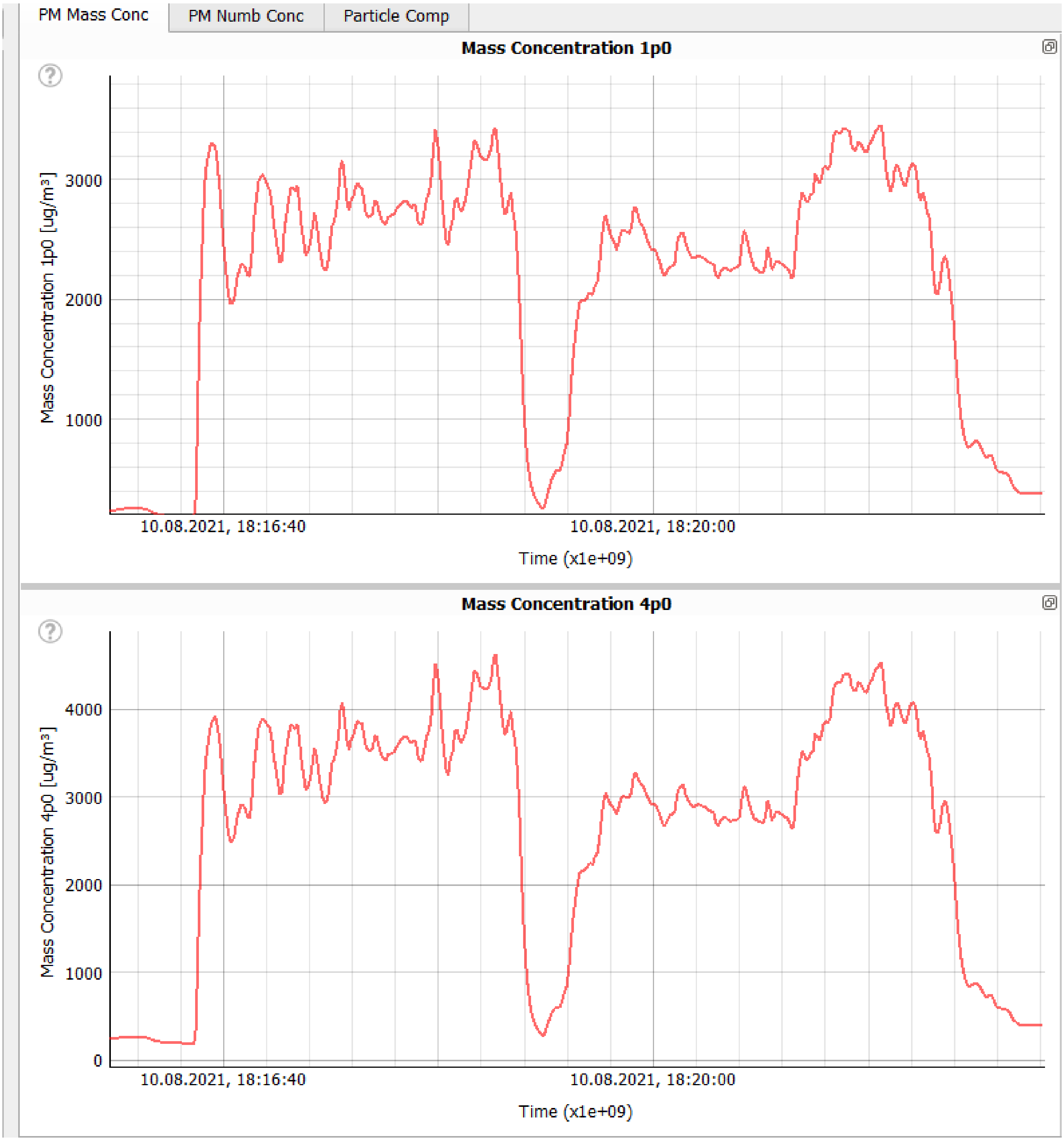
Yang, J., Yu, Q., & Gong, P. (2008). Quantifying air pollution removal by green roofs in Chicago. Atmospheric Environment, 42(31), 7266–7273. https://doi.org/10.1016/j.atmosenv.2008.07.003

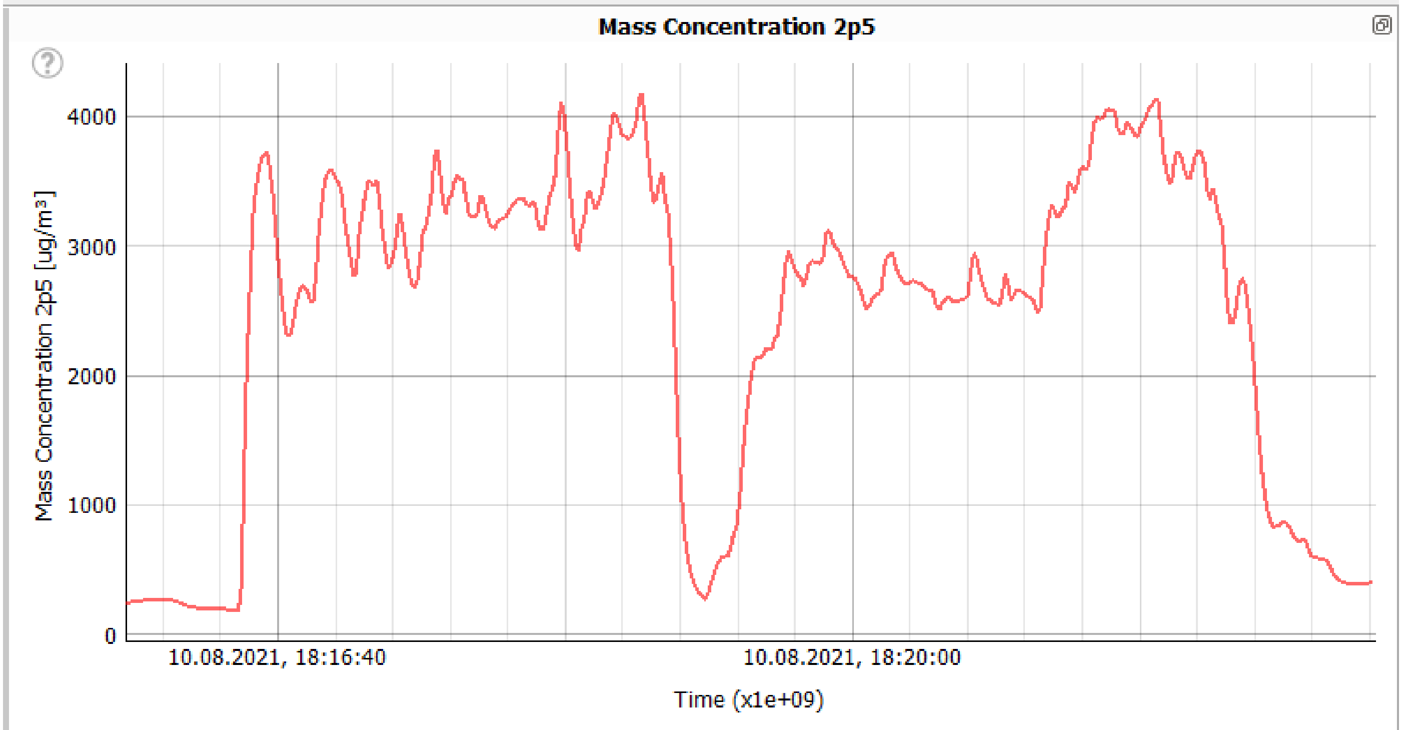
Zhang, X., Zhang, W., Yi, M., Wang, Y., Wang, P., Xu, J., Niu, F., & Lin, F. (2018). High-performance inertial impaction filters for particulate matter removal. Scientific Reports, 8(1). https://doi.org/10.1038/s41598-018-23257-x

# Appendix I:
# Test data

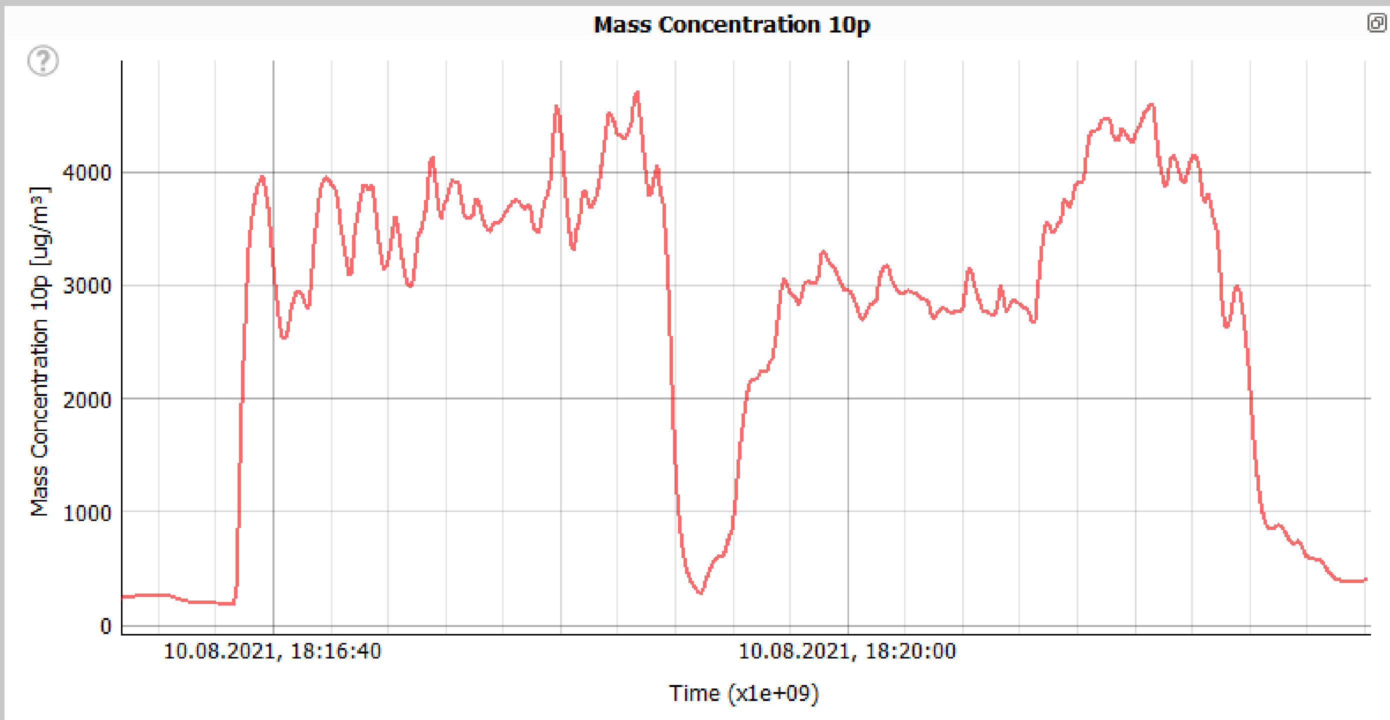
## Ventilation grille filter

*Wind velocity: 1.7 m/s*
*Test: 1*





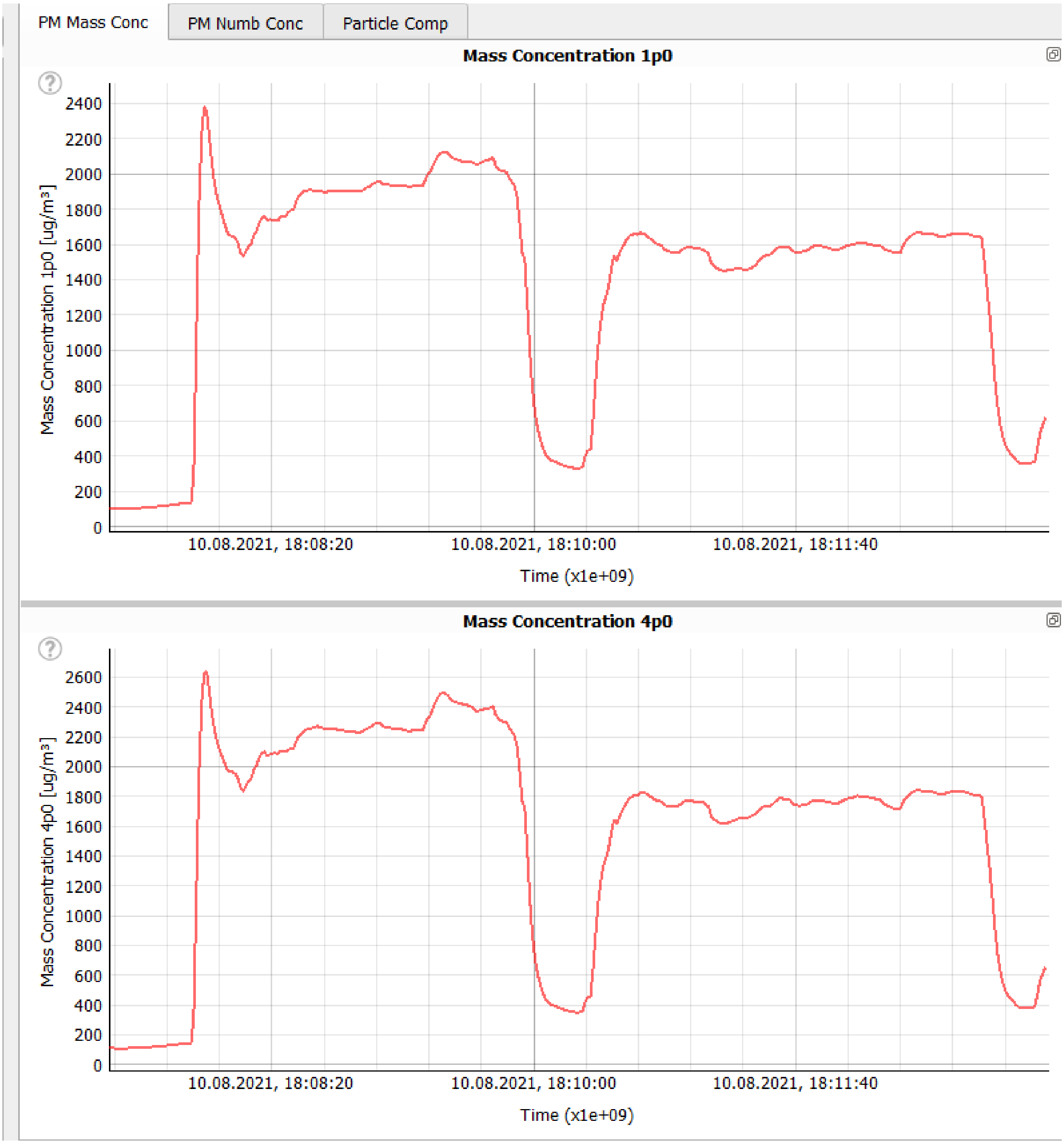
Mass Concentration 2p5
Mass Concentration 2p5 [ug/m³]
0
1000
2000
3000
4000
10.08.2021, 18:16:40
10.08.2021, 18:20:00
Time (x1e+09)

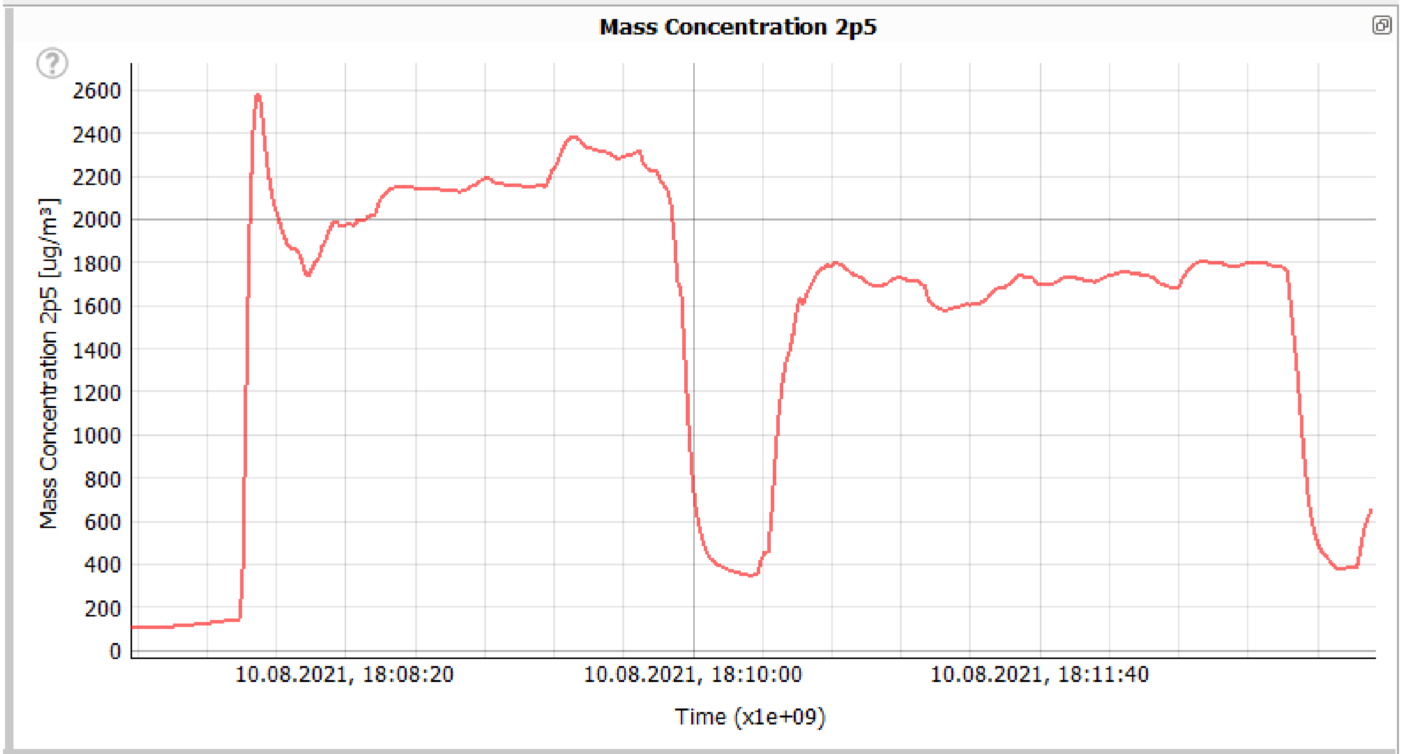



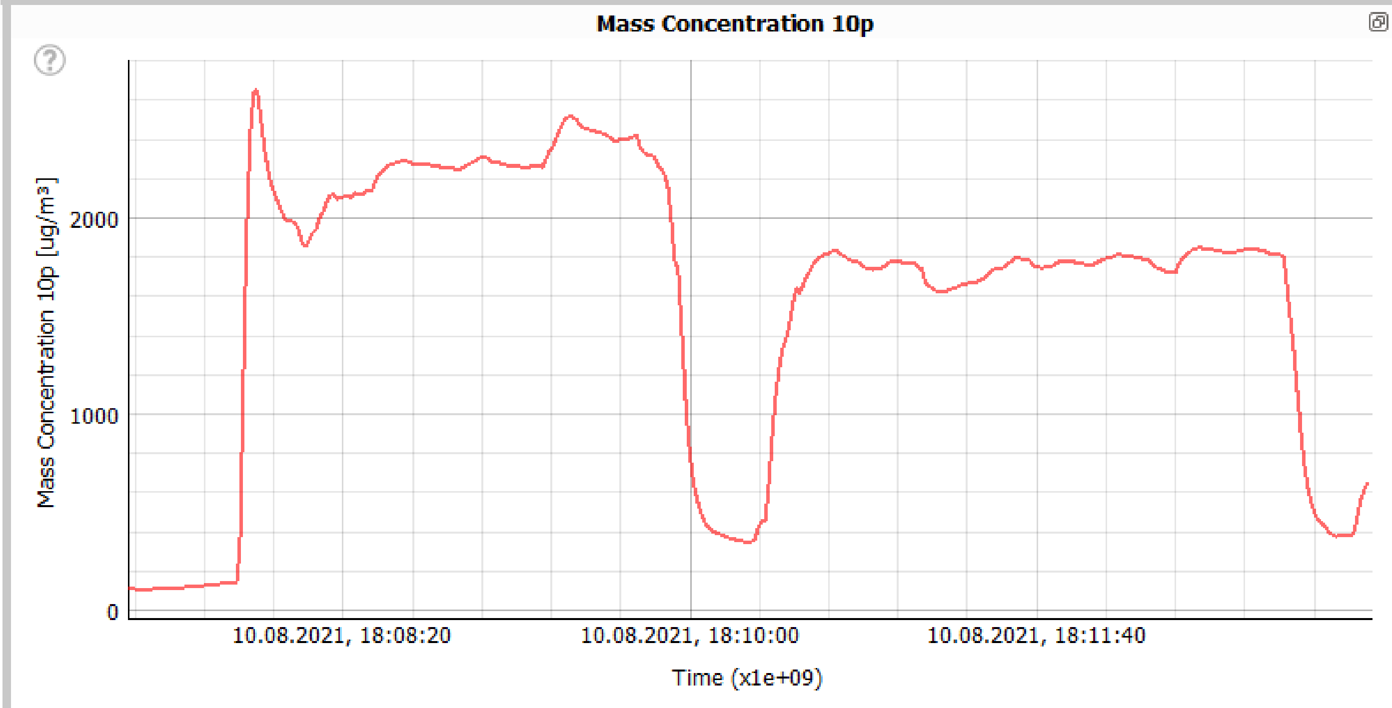
Mass Concentration 10p
Mass Concentration 10p [ug/m³]
0
1000
2000
3000
4000
10.08.2021, 18:16:40
10.08.2021, 18:20:00
Time (x1e+09)

## Ventilation grille filter

*Wind velocity: 3.3 m/s*
*Test: 1*

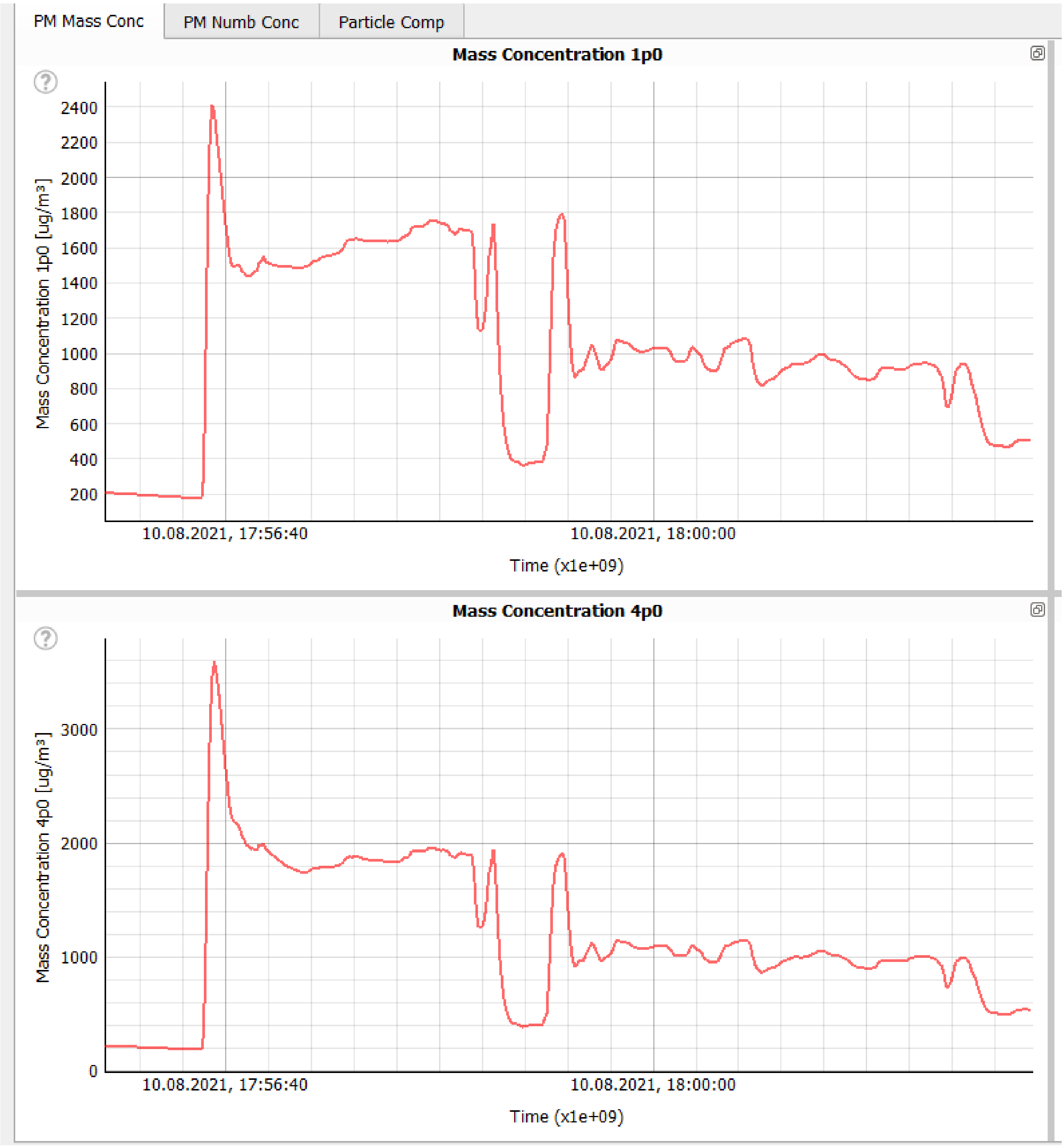


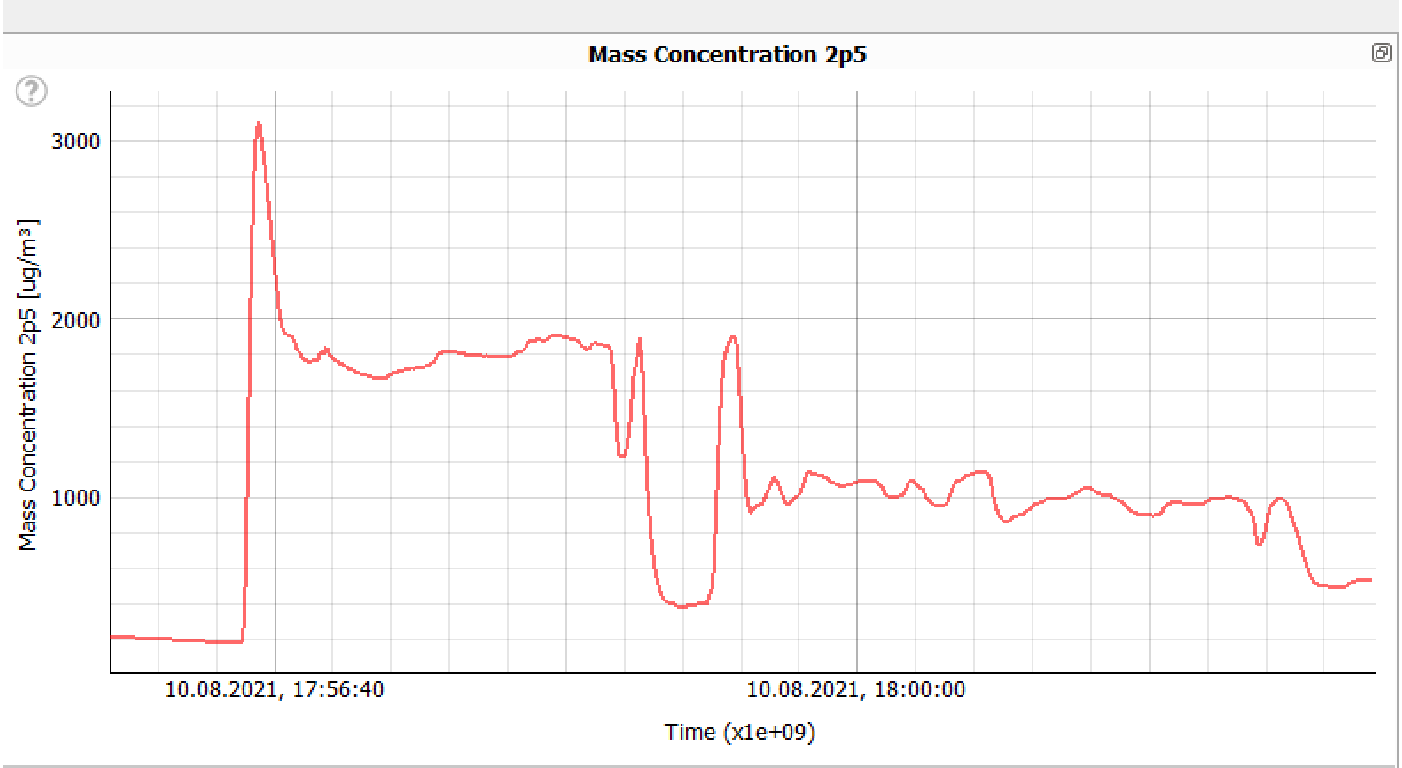

Mass Concentration 2p5
Mass Concentration 2p5 [ug/m³]
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
10.08.2021, 18:08:20
10.08.2021, 18:10:00
10.08.2021, 18:11:40
Time (x1e+09)

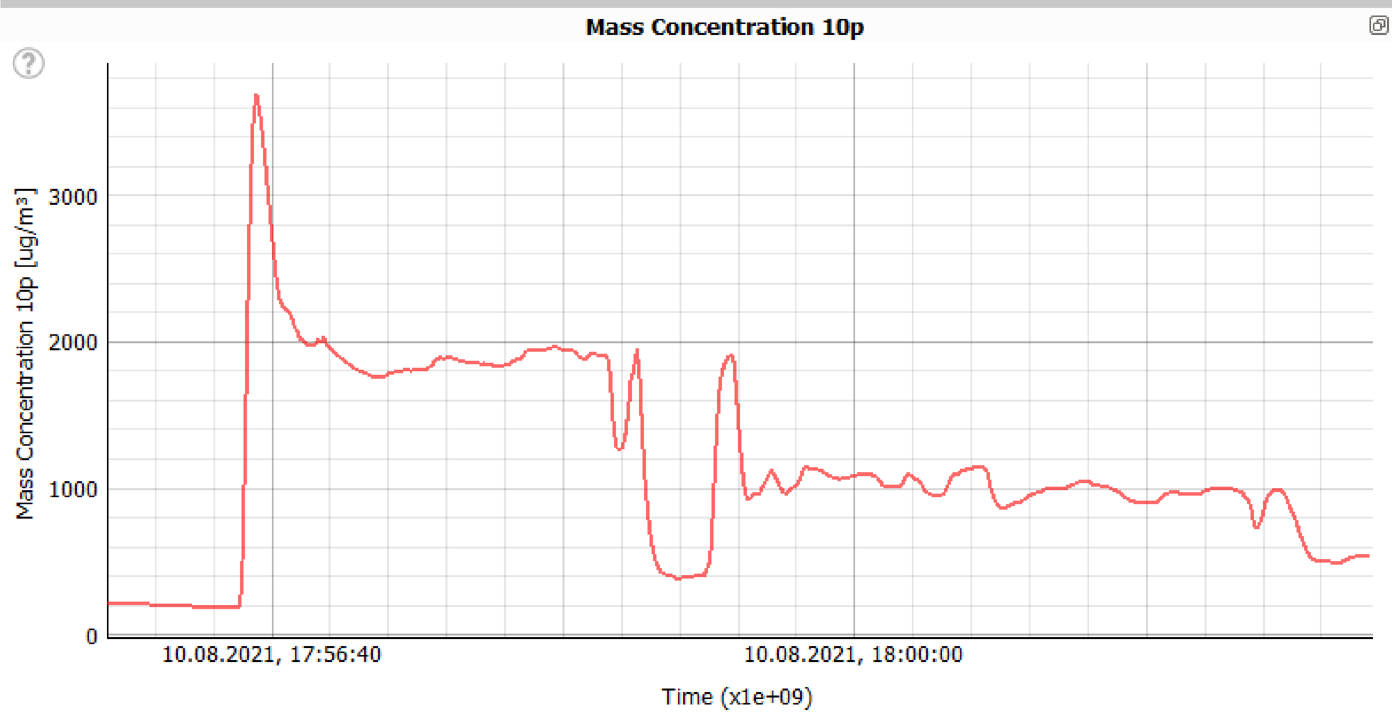

Mass Concentration 10p
Mass Concentration 10p [ug/m³]
2000
1000
0
10.08.2021, 18:08:20
10.08.2021, 18:10:00
10.08.2021, 18:11:40
Time (x1e+09)

## Ventilation grille filter

***Wind velocity: 4.8 m/s***
***Test: 1***




Mass Concentration 2p5
Mass Concentration 2p5 [ug/m³]
3000
2000
1000
10.08.2021, 17:56:40
10.08.2021, 18:00:00
Time (x1e+09)


Mass Concentration 10p
Mass Concentration 10p [ug/m³]
3000
2000
1000
0
10.08.2021, 17:56:40
10.08.2021, 18:00:00
Time (x1e+09)