THE PROSPECT OF LIVING FILTERS

Reducing building sector energy demands by improving indoor air quality

EN FRAMTID FÖR LEVANDE FILTER
Minskat energibehov för byggnader genom förbättring av luftkvalitén innomhus

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Abstract

Today people spend all the more time indoors. Asthma, allergies and Sick Building Syndrome (SBS) are affecting an increasing number of people. The remedy for all these affections has long been to increase the volume flow of outdoor air in the ventilation but at the same time cities all over the world are struggling with air pollution and smog rising above endangering levels. Living filters present a new solution where part of the indoor air can be purified and recirculated in a building. This project has compiled research on the area to describe the how and why concerning air purification by plants. Independent research conclude that plants can reduce most hazardous chemical agents in the air.

Climate change, global warming and increasing demands on energy performance induces a race for countries and companies to improve energy efficiency in all sectors. To the building engineering sector living filters presents a unique solution to cut ventilation energy loses. A powerful simulation tool IDA ICE was used to estimate the energy saving capacity when a living filter is applied in the lunch room of an office floor. Another simulation software; Comsol Multiphysics was used to illustrate the aspects of ventilation flow when a living filter cabinet is deployed in a room. The simulation results show that for three living filter cabinets each measuring 0.7×0.8×1.73 cm the buildings energy usage is reduced with more than the living filters use to operate. The single room simulations then show how a living filter can be accommodated with both mixing and displacing ventilation. However, these simulations also illustrate the importance of the living filters placement to achieve maximum ventilation efficiency.

The conclusions from this work are that living filters can reduce building sector energy demands and provide significant indoor environmental benefits. The main issue for using living filters is identified to be building regulations putting strict demands on outdoor air flow and that the hygienic function of each living filter must be verified before it may replace outdoor air.
Acknowledgements

I would like to express my gratitude to Stefan Lindberg for introducing me to the prospects of living filters and Kjell Blombäck for making this project possible to realize. All other consultants at Ramböll in Umeå deserve a thank you for all intelligent questions and experienced insights empowering this thesis. Of those of you not mentioned by name, none are forgotten.
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1 Introduction

The Earth is one massive air-system where pollution comes from geological and man-made emissions and purification is taken care of by oceans and natural flora. Humidity is controlled by temperature and pressure. If this system could be duplicated in a small scale, say a building, what is to say the environment can not be controlled. This was the idea of Bill Wolverton as he conducted plant studies for NASA’s space station applications and his studies built the foundation for an innovative Swedish patent *Levande Filter®* [1].

1.1 Background

Today people spend all the more time indoors, especially in larger cities up to 90 % of time is spent at home, school or work, indoors [2]. This way of life increases the requirements of a good and hygienic indoor climate. A consequence of traffic, industrial facilities and construction sites is the severe amount of pollutants continuously released into the air, everywhere. Air pollution is estimated to cause 2,9 million deaths around the globe annually [3]. When a building is ventilated outdoor air passes through a course and a fine mechanical filter before entering the ventilated zones where people are. Other sources of air-borne chemical pollutants are building materials, including fabric, paint and some equipment, such as a printer or most furniture.

1.2 Market Analysis

Living filters effectively target two separate issues in modern society:

Asthma

Asthma and air borne allergies are a common occurrence and all the more common today as dust and other indoors pollution affect our airways. Urbanization and increasing outdoors pollution is believed to be attributed to 15% of all cases of childhood asthma in Europe [4]. Since so much time is spent indoors an inevitable conclusion is that supply air to buildings in polluted areas such as cities are insufficient purified by the ventilation system. Asthma is only one complication caused by air pollution in our vicinity and the general methods of treatment and prevention so far are medication [5].

Building Energy Usage

The building sector comprises about 40% of Sweden’s total energy usage [6]. In a building, heating and ventilation are two major posts of energy consumption. Outdoor air is pre-treated in a heating or cooling battery and often some heat regeneration unit before supplied to the ventilated zones. Heating and cooling of supply air have so far been an inevitable energy cost in the building sector. In a mechanical ventilation system the power output demand on the fan unit is increased by all resistance and pressure drops in the system caused by filters, heat regeneration, silencers, valves etc [7]. This power demand also increases
with the volume flow in the system. Today the technical development in the area have focused on products with higher efficiency and lower pressure drops, however, almost no development have been put into reducing the volume flow.

Living filters so poses a combined solution for two aspects of problematic development with the modern world.

1.3 Purpose and Goals

The purpose of this thesis is to evaluate local- and global advantages of integrating a living filter in a buildings ventilation system.

The goal is to present Ramböll with an environmental technical solution for ventilation with potential to provide spear head competitive knowledge for their consultants.

1.4 Scope and Limitations

Living filters is merely one solution among a vast diversity of biological filters with different appearance and function. The focus of this project is whether properties of a living filter can reduce building energy usage and improve indoor air quality.

1.5 Question Formulation

- How is the energy performance of a building improved when a living filter is integrated in the ventilation system?
- Will a living filter complement to the ventilation system yield a higher indoor air quality?
- Can a living filter effectively serve as a complement to commercial ventilation without being integrated in the system?
2 Living Filters

Living filters uses plants, artificial sun light and a high pressure watering system to clean air from pollutants. The system is considered dynamic, meaning it forces air through an enclosed volume where the purification occurs. Household plants by themselves are considered a static system, they absorb compounds in their immediate vicinity but does not effect the air on the other side of the room. Thus the definition is:

- **Static system**
  A considered object occupies a space where the majority of air movement is due to natural convection, buoyancy effects and such, where air velocity is low and the object only affects the air in its immediate vicinity.

- **Dynamic system**
  A considered object occupies an enclosed space of size so all air inside may be considered in contact with the object and the air is forced through the space by an external force.

2.1 Function

Air is being drawn into the filter through a top opening then passes through a dense vegetation of plants. A watering system sprays pressurized water through a nozzle mounted in the container ceiling making fine water particles rain down through the filter and into the soil at the bottom. The showering character of the watering system binds quarts dust and other particles as well as washes the plants leaves clean. The increased humidity makes the plants more prone to absorb gases since the stomata, the cleave openings in the leaves, can be open more without dehydrating the plant [8]. Absorption of gaseous pollution agents is a unique attribute for each plant species and takes place in the stomata on the underside of the plants leaves. Thus the rate by which gases can be absorbed is directly proportional to the total leaf area in the living filter. The reduction of particles is mainly a mechanistic effect from the watering system, creating a humid environment where particles attach to each other as well as to the vegetation as they pass through the filter. As the watering system washes the vegetation clean the captured particles end up in the soil where they may contribute to nurturing the plants.

The humidification by injection of fine water droplets is described by equation 2.1.1. Practically it can be viewed as the mass flow ratio between water from the watering system and air flowing through the filter added to the absolute humidity of the incoming air. The water contents of the air is naturally defined as water mass contents per kg dry air, thus

\[ x_2 = x_1 + \frac{\dot{m}_{\text{water}}}{\dot{m}_{\text{air}}} \]  

(2.1.1)
x_2 gives the absolute humidity after humidification by the watering system. The enthalpy after humidification is be described in a similar manner by equation 2.1.2 as

\[ h_2 = h_1 + \frac{\dot{m}_{\text{water}}}{\dot{m}_{\text{air}}} \cdot h_{\text{water}}, \]

(2.1.2)

where \( h_1 \) is the enthalpy of the air before humidification and \( h_{\text{water}} \) is the enthalpy of the injected water [9]. With absolute humidity and enthalphy the temperature of the air after humidification can be found in the Mollier diagram in appendix A. From the physical principle of equation 2.1.2 the living filter may actually control the temperature of the passing air with with a few degrees by adjusting the temperature, and thus the enthalpy, of the supplied water. Excess heat in buildings is sometimes classed as a pollution in ventilation context and something a living filter can remove to a limited extent. This cooling effect makes the air from a living filter suitable for both mixing and displacement ventilation. Day light and artificial sunlight combined provide the plants with enough energy to absorb flue gases and produce oxygen all day round. A long term study by Prof. Thofelt showed how a living filter can reduce the CO\textsubscript{2} contents of the filters outgoing air to 300-350 ppm which relates to outdoor air of very high quality, better than in most cities. The CO\textsubscript{2} contents of the intake air to the living filter in this study varied from 500 - 1000 ppm [10].

### 2.2 Plant air purifying Properties

Since B. Wolverton’s experiments in 1989 [11] several studies have been conducted on the subject of air purifying plants and some of them specifically on living filters.

- **CO\textsubscript{2}**
  
  Carbon dioxide, CO\textsubscript{2}, is exhausted through breathing by most living things. It is also a product of carbon combustion in oxygen. This makes CO\textsubscript{2} our most common agent of gaseous pollution. CO\textsubscript{2} background levels are determined to be 300 ppm in forest areas and 500 ppm in major cities. The hygienic limit for indoor air is determined by Swedish building regulations to 1000 ppm.

  Household plants act as a sink for CO\textsubscript{2} according to Persson and Olander [12, 13]. At the concentration of 400 ppm *Spatiphyllum* absorbs 0.05 g CO\textsubscript{2} h\textsuperscript{-1} m\textsuperscript{-2} leaf area at 4000 lx and 0.1 g CO\textsubscript{2} h\textsuperscript{-1} m\textsuperscript{-2} at 8000 lx. With the concentration 1500 ppm CO\textsubscript{2} the sink was found to be 6 g CO\textsubscript{2} h\textsuperscript{-1} m\textsuperscript{-2} for *Schefflera* and 4 g CO\textsubscript{2} h\textsuperscript{-1} m\textsuperscript{-2} during daylight of 590 lx and outdoor CO\textsubscript{2} concentration conditions of 450 ppm [14].
• **Particles**  
Particles are constantly generated from people and animals as microscopic pieces of skin, hair and dirt fall off our bodies. Fine grains of sand, soil, quarts and other dust are also particles which can be stirred and become airborne by wind or peoples activity. As we breath the particles get stuck in our airways and lungs where they may cause anything from a dry throat to pneumonia.

Particles in the size >25 - >0,3 µm can be absorbed with a capture rate of 68% according to measurements at Berendsen Textil & Service AB performed by SCA Forest Products AB/SCA Hälsan [15]. These measurements were performed on an entire living filter of dimensions 0,7×0,8×1,73 m and not individual plants. The ability to capture particles is mainly a mechanistic effect of the watering system in the living filter.

• **Benzene**  
Benzene is the simplest aromatic hydrocarbon and a common occurrence in gasoline and other crude oil products, thus the substance can be found in exhaust gases from fossil fueled vehicles. Incomplete combustion of biomass can also result in the forming benzene rings. The substance is used in the polymers industry and can be found in some plastics. Exposure to benzene may cause cancer, bone marrow- and cardiovascular diseases.

The ability to remove Benzene was studied in a static system where the results are presented as removed mg m⁻² leaf area. For *Peace Lilly* the removal rate is 52 mg m⁻² and for *English Ivy* the value is 104 mg m⁻² during a 24 hours exposure period[11].

• **Trichloretylene**  
Trichloretylene (TCE) is a common industrial grease solvent. It is clear, non-flammable and water soluble, most commonly found in industrial appliances or as a water contaminant. Long term exposure is reported to cause kidney cancer and high demands are placed on ventilation flow when TCE is used in industrial appliances.

*Spatiphyllum* was tested as a sink for Trichloretylene during a 24 hour exposure period in a static system. The concentration was 0,126 ppm initially and measured to 0,097 ppm after 24 hours [11]. This indicates a reduction of 23%.

• **Formaldehyde**  
Formaldehyde (FAD) is an important precursor to many materials and chemical compounds. Most building materials release FAD to the sur-
roundings with a flow that decreases exponentially with time. It is also an intermediate in combustion of carbon and thus occurs in natural processes but is also found in cigarette smoke and exhaust gases from combustion engines. For most people eye- and air-ways irritation from FAD is temporarily and reversible though FAD can cause both asthma and allergies.

In a dynamic system the Formaldehyde sink of *Schefflera* was found to be 0.6 mg FAD h⁻¹ m⁻² leaf area during normal indoor FAD- and daylight concentrations of 0.5 mg FAD m⁻³ and 590 lx [14].

- **Cigarette Smoke**
  Cigarette smoke contains approximately 4000 different chemical compounds of which many are toxic or carcinogenic. Some of the compounds found in cigarette smoke such as Acetone, Benzene, Formaldehyde, Toluene and Carbon Monoxide are tested individually for the absorption ability of plants but the ‘cigarette’ mixture of gases has also been tested itself.

On Værnes airport in Norway a living filter was used to separate a smoking and non-smoking area of a restaurant. The living filter reduced both bio aerosols and particles from cigarette smoke. However, the foul air needed several passes through the filter to be completely cleansed from toxins [16]. Particle reduction in cigarette smoke was measured to supersede 60% in one pass through the living filter, using a CLIMET CL-500 [17].

### 2.3 Components

The living filters come in different size and shapes but the systems design is always the same. A few key components and functions are found in all installations and vital for the system. These are pointed out in figure 1.
Figure 1: Schematic of a living filter with key components pointed out.
1. **Lamp**
To ensure sufficient lighting for the plants regardless of location and sun irradiation led lamps provide artificial sun light at 6000 K. The light is on all day and thus prevents unwanted blooming in the plants [8]. The light intensity on the highest plants leaves is approximately 5000 lx.

2. **Watering System**
All living filters have a watering system equipped with a spray nozzle which delivers water with a showering character from the top of the filter. This helps capture particles, clean plant leaves and adjust air temperature and humidity. The watering system can be connected to the tap water system of the building or be supported by a refillable water tank.

3. **Fan**
The air flow through the filter is controlled by a fan. The small stand-alone modules uses a 12 V radial fan at the bottom of the filter where the outlet is. Living filters integrated with the building ventilation system uses the duct fan of the Air Handling Unit, AHU. Since the fan regulate the flow velocity of the air through the living filter it is crucial that correct settings are maintained.

4. **Plants**
The filter contain a variable setup of plants with air purifying properties. The plant species configuration can be selected for the type of air the filter is supposed to clean.

5. **Container**
In order for the living filter to work effectively the plants must me sealed in a container where the air can be forced through in a manner that amplifies capture of particles and absorption of undesired gases. A glass cage meets these requirements and also gives the filter an aesthetic value. The clear glass also exposes the plants to natural light which decreases the need for lamps and thus the operational power requirements.

### 2.4 Main Products

The living filters can conveniently be divided into two main groups.

1. **Stand-alone units**
These products are relatively small units with an effective volume of approximately 0.6 m$^3$, similar to the glass cabinet shown in figure 1 above. They can serve as ventilation for a 70 - 100 m$^2$ area, depending on the room layout. The watering system is either connected to the buildings.
tap water piping or served by an internal water tank of 40 liters which is refilled manually [18].

2. **Fully integrated systems**
   A fully integrated system is when the building's conventional ventilation system uses a living filter to purify air. The most common configuration is when the living filter purifies indoor air which is recirculated and thus works as a complement to the supply air from outdoors. This can reduce the need for outdoor air down to the minimal requirements established by building regulations [10].

2.5 **Reference Installations**
Among the studied installations two have been chosen for closer examinations. Both facilities are located just north of Sundsvall. One installation uses twelve stand-alone products and the other reference installation at Sundsvall-Timrå (Midlanda) Airport, has a living filter fully integrated in the ventilation system.

2.5.1 **Njurunda Church**
In an old church north of Sundsvall an intervention was done to prevent variations in temperature and humidity from ruining the antique organ as the changes caused the wooden parts to swell and shrink continuously.

**Before Living Filters**
The church is an old building with poor insulation and single pane windows. The ceiling is eight meters above floor level in the large main room and apart from living candles and people the heat source is water borne radiators located under the most of the benches. Buoyancy forces causes for the warm air to rise forming a temperature gradient from the ceiling down to the floor and very stationary air. The ventilation was powered by natural draft and almost without effect. The organ is located on the grandstand four meters above the main floor. The wood and the metal pipes of the cold instrument became a victim for condensation from the warm air close to the ceiling. The church is populated once or twice a week for masses but empty the rest of the time and thus, in the interest of saving energy and money, the heating is regulated to have the church warm only when a mass is held. The indoor climate was accused of being cold, damp and drafty during masses, although there was almost no air circulation. This is a common effect of the felt thermal radiation from a person to the ambient environment when surface temperatures of walls, floor and ceiling are low.

**With living filters**
Twelve stand-alone living filters cabinets, each with a container volume of approximately 0.6 m$^3$, were installed and connected to the tap water piping system.
A flow velocity of 1 m/s gives a total volume flow of 7.2 m$^3$/s where the air temperature is decreased with 1 °C in the filter and the outgoing air has a constant relative humidity of 30 - 40 % all year [19]. Figure 2 shows the temperature variation as a function of height in the church before and after installation of living filters.

Figure 2: Temperature gradient in Njurunda church before (upper) and after (lower) installation of living filters [18].

As a complement to the living filters the church was also equipped with double pane windows and the heating source was changed from an oil furnace to ground heat with a heat pump. The result of these improvements are, however, not included in figure 2.

2.5.2 Midlanda Airport

The living filter at Sundsvall-Timrå Airport was installed when the new terminal building was constructed in 1997 and has been operational since then. The filter is seen in figure 3. It consists of nine blocks, each with a volume of 38 m$^3$ and is designed to serve the departure- and waiting hall of the airport. 2016 the air flow through the filter was determined to 4 900 l/s [20]. Roughly the same flow was used in 1997 when a study was prepared for the department of trade and industrial- and technological development (NUTEK) with the aim to examine the functionality of the living filters air purifying properties. Measurements were of concentrations of formaldehyde, toluene, hydrocarbons, carbon dioxide, water vapour, Volatile Organic Compounds (VOC) and particles >25 - >0.3µm. Analysis of the results show a remarkable reduction of CO$_2$ to concentrations in the range 300 -350 ppm after the living filter. Formaldehyde,
toulene and hydrocarbons all had slightly higher concentrations indoors than outside the building. The same is true for VOC and the reason is believed to be the off-gasing from the building itself, which was completed less than six months earlier. The measurements of water vapor found a constant contents of 36 % Relative Humidity (RH) from the living filter, however the RH of the outdoors was measured to 35 % between 10.45 and 11.30 that day which means no extensive conclusions can be drawn. The measurement of particles was done for six particle sizes and is displayed in table 1.

Table 1: Number of particles (units) in incoming and out-flowing air from the living filter [10].

<table>
<thead>
<tr>
<th>Diameter</th>
<th>&gt;25</th>
<th>&gt;10</th>
<th>&gt;5</th>
<th>&gt;1</th>
<th>&gt;0.5</th>
<th>&gt;0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Departure hall</td>
<td>140</td>
<td>3660</td>
<td>26900</td>
<td>485410</td>
<td>2738560</td>
<td>6621000</td>
</tr>
<tr>
<td>LF out*</td>
<td>110</td>
<td>1750</td>
<td>8220</td>
<td>94180</td>
<td>569150</td>
<td>3982000</td>
</tr>
<tr>
<td>Reduction in units</td>
<td>30</td>
<td>1910</td>
<td>18860</td>
<td>391230</td>
<td>2169410</td>
<td>2639010</td>
</tr>
<tr>
<td>Reduction (%)</td>
<td>21</td>
<td>52</td>
<td>69</td>
<td>81</td>
<td>79</td>
<td>40</td>
</tr>
</tbody>
</table>

*Air out from living filter.

The measurement of particles was performed with the watering system turned off because the used instrument Climet CL-500 register fine water droplets as particles [8]. The showering system has been shown to help capture particles in the larger categories in previous studies of a living filter [17]. The reduction of particles in the two finest categories is remarkable compared to mechanical filters.

2.6 Species

Since the early nineties the ability for plants to absorb air pollution have been thoroughly studied [11]. This ability differs both between plant- and pollution species. For a living filter to be effective against all undesired compounds found in a building the plants must be selected to provide a complete coverage. Plants with different physical characteristics are selected to effectively fill the volume in the filter. The composition of plants is also adapted to the plant species individual light needs. Species that thrive in high intensity light are placed to provide some shading for those who prefer light with lower intensity. In table 2 the species are arranged in such a manner that underbrush and household plants are found at the top of the table. After them come vines and finally trees. These are the plants used at Sundsvall-Timmå Airport, commonly known as Midlanda. Table 2 also gives the different plants individual ability to absorb gases of four different types. How well a gas agent is absorbed is measured on a scale of 0-3 where '0' means this plant can not absorb this gaseous agent. '1' means the plant can absorb this sort of gas but only to a limited extent, '2' means the plant absorbs this type of gas well and '3' means this plant absorbs this type of gas exceptionally well.
Table 2: Scientific- and English name of the plants at Midlanda. Gaseous pollution absorption ability no the scale 0-3. 0 = No absorption, 1 = Small absorption, 2 = God absorption, 3 = Very god absorption of this agent [11, 12, 13, 14, 17, 18, 21].

<table>
<thead>
<tr>
<th>Scientific Name</th>
<th>English Name</th>
<th>CO²</th>
<th>Benzene</th>
<th>TCE</th>
<th>FAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spathiphyllum Kochi</td>
<td>Peace Lilly</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Aglaonema Commutatum</td>
<td>Chinese Evergreen</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Aspidistra Elatior</td>
<td>Aspidistra (Cast Iron Plant)</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Asplenium Nidus-Avis</td>
<td>Birds Nest Fern</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Platycerium Bifurcatum</td>
<td>Stag’s Horn Fern</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Radermachera Sinica</td>
<td>Emerald Three</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Sansevieria Trifasciata</td>
<td>Mother In-law’s Tongue</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Schefflera Actinophylla</td>
<td>Schefflera</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Dracaena Fragrans</td>
<td>Cornstalc Dracanea</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Ficus Elastica</td>
<td>Rubber Plant</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Clerodendrum Thomosoniae</td>
<td>Bleeding-heart Vine</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Monstera Deliciosa</td>
<td>Monstera</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Vitis Vinifera</td>
<td>Grape Vine</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Coffea Arabica</td>
<td>Coffe Three</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Musa Acuminata</td>
<td>Banana</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Corynocarpus Laevigatus</td>
<td>Karaka</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Nolina Recurvata</td>
<td>Elephant Foot Three</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Phoenix Canariensis</td>
<td>Canary Island Date Palm</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>
The scale is relative and the '3' -value is determined by the plant with best absorbance for each of the four gases. For the four gas agents in table 2 these are:

- **CO\textsuperscript{2}**: *Scheflera* at 4.0 g CO\textsuperscript{2} h\textsuperscript{-1} m\textsuperscript{-2} leaf area.
- **Benzene**: *Mother In-law’s Tongue* at 1.0 g h\textsuperscript{-1} m\textsuperscript{-2} leaf area.
- **TCE**: *Peace Lilly* at 0.35 g h\textsuperscript{-1} m\textsuperscript{-2} leaf area.
- **FAD**: *Mother In-law’s Tongue* at 1.1 g h\textsuperscript{-1} m\textsuperscript{-2} leaf area.

The '1' -value indicates an absorbance 0 < '1' << '3' and the '2' - value is for an absorption rate between the '1' and '3' value for each agent. An absorption rate within 80% of the maximum value for each gas agent is classified as '3'. This system is not as precise as denoting the exact absorption rate for each plant, however, it greatly simplifies the equipment of a living filter [18]. Apart from the plant species displayed in table 2 there are more species with good air purifying properties, two examples are *English Ivy*, which is a category '3' for absorption of Benzene, TCE and FAD, and *Salix Viminialis* which is very good for CO\textsuperscript{2} absorption.

### 2.7 Life Cycle Assessment

A Life Cycle Assessment (LCA) was performed on one Living Filter, stand alone product of 1300 × 700 × 2100 mm with a flow of 120 m\textsuperscript{3} h\textsuperscript{-1} purified air. The assessment was made by independent consultants from the Jegelius Institute and Miljögraffen. A life cycle of 15 years was considered where the consumed power from operation was identified as the major source for emissions of greenhouse gas. Hardened glass and virgin aluminum were found to be the components contributing to most emissions of CO\textsuperscript{2} equivalents [26]. Today the product is updated and uses a smaller amount of glass and aluminum, the aluminum source is partially recycled material and the tray material is changed from stainless steel to non toxic plastic [18]. The Life Cycle screening of a living filter was compared to a standard ventilation facility using the ReCiPe LICA methodology. The ReCiPe method evaluates a series of classic factors of environmental impact (global warming, water use, human toxicity, mineral resources etc.) and analyses the pathway through which damage is done to human health and ecosystems. The analysis summarizes these aspects to a set of points which is the general environmental impact of the analyzed object. A higher score of points for an object indicates a more negative environmental impact [27]. The living filter received 20 points for manufacturing and another 105 points for 15 years operation. The equivalent conventional ventilation facility chosen by Miljögraffen received 73 points for manufacturing and another 240 points for 15 years operation [26].
2.8 Psychological effects

Plants have shown to boost a number of psychological effects on how people perceive the indoor environment. The plants contribute to a private and snug feeling as well as they reduce the sensation of stress by having a restorative, calming and positive effect on peoples mood [22]. Plants near the work space have shown to have a positive effect on employees productivity and creativity. The ability to concentrate have also been shown to improve, especially for people working more than four hours a day in front of a computer screen [23]. In a study where plants were placed in offices, the employees trouble from headache and fatigue was reduced with 30% by the intervention. Hoarseness and dry throat decreased with 30% and issues with dry skin was reported to have been reduced with 25% [24]. The study could not determine whether the reported effects were due to a physical improvement of the indoor air quality by the plants or if the results were due to psychological effects of generally increased well being from the sight of plants. Another study comparing offices decorated with plants to offices without plants found the presence of living plants to give the workers a relief from stress. The study also found the plants to have a positive impact on how well people thrive in their workplace and how well motivated they feel towards their work [25]. Figure 3 show the aesthetics of the living filter installed at Sundsvall-Timrå airport. The living filter is located in the departure hall 3 m above the ground floor and only one fifth of the living filter is seen in the figure.

Figure 3: The ventilation system integrated filter at Sundsvall-Timrå airport.
3 Theory

The necessary theory concerning the application of living filters in a building are worked over in the following sub chapters.

3.1 Building Regulations

Laws and regulations concerning buildings and ventilation are issued by Boverket and found in Boverkets byggregler, BBR. Chapter 6:25 dictates the ventilation system shall be designed so enough outdoor air can be supplied the building. The ventilation system must also be able to remove health impaling substances, humidity, excretions from people and materials as well as other pollutants that may occur [28]. The BBR also specifies certain regulations for minimum outdoor supply air to be:

- 0,1 l/(s · m$^2$) floor area of an empty building.
- 0,35 l/(s · m$^2$) floor area when someone may sojourn in the building.
- 7 l/(s · p) where p is the number of people in the building.

3.2 Ventilation

The heat transfer to or from a building is in general cases a combination of transfer through the climate shell, ventilation, infiltration and solar radiation. Solar radiation generally transfers energy to the building and the other three posts transfer energy away from the building. Infiltration is unwanted air leakage through windows, doors and other openings. The heat loss through infiltration can be described by equation 3.2.1 as

$$\dot{Q}_{\text{inf}} = \rho \cdot c_p \cdot \dot{V}_{\text{inf}} \cdot (T_{\text{in}} - T_{\text{out}}),$$  \hspace{1cm} (3.2.1)

where $\rho$ is the density of the air, $c_p$ is the heat capacity. $\dot{V}_{\text{inf}}$ is the volume flow of the infiltration, $T_{\text{in}}$ is the air temperature indoors and $T_{\text{out}}$ is the air temperature outdoors. Ventilation heat transfer can be described in a similar manner by equation 3.2.2 as

$$\dot{Q}_{\text{vent}} = \rho \cdot c_p \cdot \dot{V}_{\text{vent}} \cdot (1 - \eta) \cdot (T_{\text{in}} - T_{\text{out}}),$$  \hspace{1cm} (3.2.2)

where $\eta$ is the temperature efficiency for heat regeneration by eventual heat exchanger defined by equation 3.2.3 to be

$$\eta = \frac{T_{\text{re}} - T_{\text{out}}}{T_{\text{in}} - T_{\text{out}}},$$  \hspace{1cm} (3.2.3)

where $T_{\text{re}}$ is the air temperature of the supply flow after heat regeneration and other indexing are the same as defined above [9].
3.2.1 Heat Regeneration

The heat exchanger is a device that provides transfer of heat energy between two fluids of different temperature.

Rotational heat exchangers

These are a common type in homes or public buildings and has a very high temperature efficiency. The warm fluid passes through one half of a rotating disc with dense fibers forming a large surface area for convective heat transfer. The cold fluid passes through the other half of the disc. As the disc rotates the warm fluid transfer heat to the disc which is in turn transferred from the disc to the cold fluid. A schematic view of a rotational heat exchanger is shown in figure 4. The temperature efficiency can be as high as 90%.

The downside of this technology is a small, inevitable, mixing of the air streams and this way contaminants in the exhaust stream may enter intake stream. This problem is solved with a pressure gradient of higher static pressure on the intake side. A small stream of intake air is then used to blow the lamellae clean, sending eventual pollutants in the disc back to the exhaust side. In building ventilation applications this mainly mean smell and air borne viruses or bacteria in the exhaust air may contaminate the supply air to some small extent. This makes rotational heat exchangers a bad application for kitchen and sanitary ventilation where the concentration of smell or other pollution may be very high [29].

![Figure 4: Schematic of a plate heat exchanger](image)

Plate heat exchangers

Also called cross flow heat exchangers are a common type of recuperative heat exchanger, where the two fluids are separated at all times and there can be no
mixing. Its heat transferring mechanism is constructed from thin metal plates which forms columns with high thermal conductivity. Cold air enters on one side of the heat exchanger and travel through every other column. In between the columns with cold air, the warm air travels in opposite direction. The air streams never meet so there can be no mixing unless there is a leakage. To prevent any contamination entering the fresh air the exhaust air is set to have a slightly lower static pressure, any leakage between the air streams will thus travel to the exhaust air, not from it. Cold climate may cause frosting on the heat exchanger which primarily occurs in the ”cold corner” between the entrance of the cold air stream and the exit of the warm one, displayed to the left in figure 5 [29].

![Figure 5: Schematic of a plate heat exchanger](image)

**Return Air**
Return air means extract air is mixed with the supply air to raise the temperature of the incoming air stream. This is an efficient method to reduce the ventilation energy demands. However, any pollution removed with the extract air will be returned to the room with the supply air when the two air streams are mixed. This is a severe disadvantage and the reason why return air is only used on special occasions after a special assessment is made. Since 1994 special regulations has restricted the use of return air and the BBR [28] dictates that the return air stream must be purified in a reliable way before the mixing [7].
### 3.2.2 Ventilation Principles

The efficiency of ventilation systems are in general related to temperature and pollution concentration in the supply-, room-, and extract air. Ventilation efficiency is a measure of how effectively a pollutant is removed by the ventilation. In ventilation systems design the two concentration parameters of temperature and pollution are estimated with air flow calculations using equation 3.2.4 and 3.2.5. The temperature efficiency can be expressed as

\[
E_{\text{temp}} = \frac{T_e - T_s}{T_r - T_s},
\]

and the pollution ventilation efficiency

\[
E_{\text{pol}} = \frac{p_e}{p_r},
\]

where 'T' denotes temperature and 'p' the concentration of pollutants. The index 'e' represents extract air, 's' the supply air and 'r' denotes the room. Air change efficiency is a measure of how efficient the air in the room is renewed [30]. A main goal in ventilation systems design is therefore to use unit dimensions and placements to maximize the air change- and ventilation efficiency. This can be achieved through a few different ventilation principles.

- **Short cut ventilation**
  A "short cut" ventilation is when the incoming fresh air flows straight to the extract valve and leaves the room before mixing with the majority of the air mass. This is an undesired property of a ventilation system and important to have in mind when designing the system. This is illustrated in figure 6, the supply air moves directly to the extract valve and the air in the room becomes stagnant, pollution remains and the air change efficiency is low.
• **The Mixing Principle**  
Ventilation according to the mixed principle delivers fresh air to a zone at relatively high velocity which thus mixes well with the air in the room. This design is suitable for both warming and cooling a room with ventilation air. The high velocity of the supply air causes an effect called co-ejection which means stagnant air near the air stream is sucked into the stream as well. This effect increases the mixing of the air as is illustrated by the flow arrows to the left, underneath the supply valve in figure 7. When homogeneous temperature and pollution concentration is desired the mixed principle is often used.
• The Displacement Principle
The displacement principle uses buoyancy forces to transfer heat and pollution out of the room. Air is supplied close to the floor at a temperature lower than the average of the room. Electrical equipment, people and lighting warms the air in the room which rises to the ceiling where the outlet valves are located. This system is suitable for cooling a room with ventilation air but has a low efficiency if the supplied air is warmer than the average of the room. The flow route is illustrated by figure 8.

![Figure 8: Displacement principle ventilation](image)

• The Piston Principle
The piston principle supplies air at one side of the room and extracts air at the other. This causes a laminar, piston like, air flow through the room and can be viewed as an extreme case of displacement ventilation. The piston principle is mainly used in special applications like clean rooms since a low air velocity, necessary for laminar flow, requires a very large supply and extract area. In figure 9 the laminar flow is illustrated as rows of vectors. A small disturbance in the laminar flow is caused by the occupant in the room.
Ventilation systems can also be divided into two main groups.

**Constant Air Volume**

Constant air volume flow (CAV) is a simply regulated ventilation system. As the name indicates the air flow is constant, only the supply temperature and occasionally the humidity is regulated. The simplicity of the system makes it suitable for homes especially since the ventilation load remains constant over daily- and weekly cycles. CAV ventilation is also suitable with all ventilation principles and require no active adjustment of the valves.

Living filters can also be viewed as a CAV system since the flow through the filter is constant. This makes manual adjustment of an existing CAV system easy when a living filter is applied so the two systems work together yet independent to ventilate a building.

**Variable Air Volume**

Variable air volume flow (VAV) ventilation systems are more complex but also more adaptable. The air flow through each valve can be adjusted depending on the needs of each zone. Most common regulating factors are CO$_2$, temperature, occupancy or concentration of some chemical agent, an application mostly used in industries dealing with volatile substances. A VAV system is also suitable for offices, restaurants and other operations where the ventilation demand varies over daily- and weekly cycles.

Living filter appliance to a building with VAV ventilation is both simple and efficient. The living filter will constantly reduce pollution in the ambient zone.
and the VAV regulation sensors will decrease the ventilation flow accordingly, down to a specified minimum.

### 3.3 Sick Building Syndrome

Sick Building Syndrome, SBS, relates to a number of symptoms caused by poor indoor climate. The name SBS is somewhat misleading since the building itself is not sick but rather cause some people to display symptoms of illness. These can be headache, nausea and infections in the respiratory system. The cause of SBS is believed to be a combination of air-borne pollution such as particles, volatile organic compounds (VOC) and microorganisms. All these factors can be related to poor or insufficient ventilation. The extract air is supposed to remove air and pollution with it but sometimes pollution is found in the supply air as well. This illustrates a problem for conventional ventilation which is dependent solely on mechanical filters. If the air could be purified in-house and thus the climate shell of the building could serve mainly as protection from the pollution outdoors [31].

### 3.4 Mechanical Filters

Mechanical filters are used in ventilation to purify incoming and outgoing air from particle pollutants. The diameter of these particles vary in the range 0.01 – 100 µm. In comfort installations the filters normally separates particles with diameter larger than 5 µm [32]. Filters are normally placed before the heat exchanger in a ventilation system to prevent unnecessary wear or an insulating, sinter-like build-up on the heat transferring surfaces. The loss of dynamic pressure over a clean filter is, the filter specific, initial pressure drop which is increased further as the filter is filled with particles and becomes more dense [30]. From its initial value the pressure drop over a mechanical filter can increase with 100 – 200% and the filter will eventually need to be replaced. If a filter is used for too long without cleaning or replacing it will eventually start to release previously captured particles. Normal service intervals for mechanical filters are 6 – 18 months [7]. To prevent this service from being neglected it is checked during a compulsory ventilation control (OVK) which is demanded by building regulations [33].

Latest standard for filter classification distinguishes four different filter classes based on particle transmittance [34]. A coarse filter catches < 50 % of particles in the range of 0, 3 – 10 µm [35]. Fine filters constitute the last three classes as follows:

- ePM10 captures particles of diameter 0.3 – 10 µm.
- ePM2.5 captures particles with 0.3 – 2.5 µm diameter.
- ePM1 captures particles with diameter in the range 0.3 – 1 µm.
For these three classes the capture rate must be at least 50% of the particles entering the filter. The fine filters are then divided into sub classes by capture rate efficiency which is reported in percent of particles captured, rounded in 5%. Most filters classed as F7 by the old standard SS-EN 779 has an initial pressure drop of 70 – 120 Pa and qualify as ePM1~ 65%, ePM2.5~ 75% and ePM10~ 90% [36]. The pressure drop over a filter reduces the efficiency of the system by demanding more fan power. Thus a filter with high capture rate and low pressure drop is desirable [9]. To capture gaseous pollutants a special mechanical filter, or filter membrane, of active carbon is required [7]. In Umeå the concentration of PM10 is continuously measured by Umeå Kommun [37], which presents a annually mean value of 13 µg/m³ air, and Naturvårdsverket [38] which presents fluctuations in the range 5-235 µg/m³ air on June 8, 2018.

3.5 Biology

The diversity among plant species is immense. However, most plants function in the same way and consist of the same parts. In a living filter appliance both physiological and mechanistic properties of plants must be accounted for.

3.5.1 Physiology

All plants consist of mainly the same parts. Of the plants used in a living filter the parts of the plants and their separate function are mainly the same.

Roots
The roots provide the plant with a stable foundation by forming a firm grip to the ground. The roots also serves the purpose of absorbing water and minerals for the plants needs through a process of osmosis. Nutrients and minerals are made available for absorption by microbiology in the soil.

Stem
The stem is the main body of the plant. It determines how tall and thick the plant grows. The stem is also important as a transport way for water, and nutrition and energy between the different parts of the plant through a combination of osmosis and capillary force.

Shoots
Some plants form shoots as a small branch between the main stem and the leaves. On most species the shoots also contain chlorophyll and cleave openings, thus they may contribute to energy production and gas absorption to some small extent. This has, however, not been studied thoroughly but rather neglected from most studies.

Leaves
In air purification appliances the leaves are the most important part of the plant and most desirable properties are direct proportional to the plants leaf
area. The leaves contain the majority of the chlorophyll which is the reactive pigment that absorbs energy from light. The cells in the leaves are organized so that the highest chlorophyll concentration is directed towards the upper side of the leaf, giving it a more dark green colour than the back side which is generally turned down towards the ground. The leaves also contain a network of veins which is used to transport nutrition, water and energy between the leaf and the rest of the plant. On the under side of the leaf the stomata, the cleave openings, are located. These are like doorways into the leaf which the plant can open and close to control the in- and outflow of gases. CO$_2$ flows into the leaf to be synthesized in energy production but other gases also follow and may be consumed. O$_2$ and H$_2$O are the major byproducts from the photosynthesis and these are released through the stomata as well. The H$_2$O is transferred to the air through evaporation which makes the transfer rate directly proportional to the relative humidity in the ambient air. The opening and closing of the stomata is regulated by the plants water economics, thus the rate at which gases are absorbed becomes proportional to the relative humidity as well. Higher relative humidity in the ambient air makes it possible for the stomata to stay open longer without dehydrating the plant and as the stomata stays open longer, more gas can be absorbed. This is one of the keys to the functionality of a living filter.

3.5.2 Photosynthesis

Sun light is electromagnetic energy which reaches the Earth with a power of 1360 W/m$^2$ above the atmosphere and can vary in the range of 900 - 0 W/m$^2$ on the ground due to clouds and diffusion in the atmosphere [39]. Light can be reflected, transmitted or absorbed when it meets matter and the wavelength spectrum 380 - 750 nm is called visible light. The particles absorbing visible light are called pigments and in living plants these are chlorophyll A and B as well as carotanoids [41]. The chlorophyll is found in the plant cell organelle chloroplasts and this is where the photosynthesis takes place, the process where the electromagnetic energy in visible light is used to form biomass, oxygen and water from CO$_2$ and water. This is illustrated by equation 3.5.1.

$$ CO_2 + 2H_2O + \gamma \rightarrow (CH_2O) + O_2 + H_2O, \quad (3.5.1) $$

where $\gamma$ is photosynthetic light and the compound (CH$_2$O) is a simplified formula for organic matter generated by the photosynthesis. H$_2$O is written on both sides of the reaction, however, it is not the same molecules as H$_2$O is both degenerated and formed from this cyclic process as shown in figure 10 [40].

Light Reactions

Light is absorbed by the chlorophyll in the chloroplast where each photon excite a single electron which is absorbed by a primary electron acceptor. The electrons are replaced from the water molecule on the left side of equation 3.5.1 and the H$_2$O is split into oxygen and protons. The diffusion of H$^+$ from the thylakoids, the membrane sacks, of the chloroplast to the stroma, the fluid part, powers the
synthesis of Adenine-Tri-Phosphate, ATP. Again electrons are excited by photons and these are used for the reduction of Nicotamide-Adenine-Dinucleotide-Phosphate, NADP\(^+\) to NADPH. Thus the result of one light absorption cycle are the universal chemical energy carriers used by biologic matter, one ATP and one NADPH molecule. [40, 41]

**Calvin Cycle**

Carbon compounds are produced in the stroma of the chloroplast by incorporating CO\(^2\) with the enzyme Ribulose-Biphosphate-Carboxylase-Oxygenase, RuBisCo. Six ATP and six NADPH are used to produce six glyceralddehyde-3-phosphate molecules. Of these 3-carbon compounds, one molecule is accumulated as biomass and the other five are synthesized along with three more ATP to reproduce the CO\(^2\) acceptor Rubulose-Biphosphate, RuBP for the cycle to start anew.

![Figure 10: Schematic view of the two cyclic reactions of the photosynthesis.](image)

**Variations of photosynthetic mechanisms**

The photosynthetic process described above is used by plants of the C3-metabolism category, named so because the Calvin Cycle produces one 3-carbon compound per turn. Plants in the C4-metabolism category first fixate CO\(^2\) as a 4-carbon compound through the Hatch-Slack-cycle to preserve water before reforming it to a 3-carbon compound through the Calvin cycle. Crassulean Acid Metabolism (CAM) is perform by plants in the CAM-metabolism category. These plants fixate CO\(^2\) during the night and utilize only the light reactions during the day.
The CAM-plants generally grow very slowly and are specially adapted to dry and warm climates. The C4-plants are also more adapted to warm, dry climates than the ones using C3-metabolism. The C3-metabolism, however, is the most energy efficient sort of photosynthesis.

Living filters use only C3-metabolism plants since these have a much more efficient way of absorbing CO$^2$. The climate in a living filter can be controlled to suit these plants with poorer water economy which results in a controlled humidification of the air passing through the filter.
4 Method

The methodology of this project was focused around two central tasks. First a review of the research in the area of air purifying properties of plants and the extent of air pollution effects on people was conducted.

In an engineering approach the functionality of living filters was simulated with two powerful simulation tools. First IDA ICE was used to determine reasonable energy saving prospects with living filter appliance to an existing building. Moreover the properties for a living filter to ventilate a room and the tendency for short cut ventilation to occur was simulated with Comsol Multiphysics 5.2.

4.1 IDA ICE Simulations

IDA ICE was used to compare the energy performance of one floor in a multi story building when equipped with living filters and not.

The CAD plans for the building was imported to IDA to use as a drawing map when constructing the building. The CAD plans are seen as colorful drawings on the ground in figure 11. The seventh floor of the eight story building is investigated for the energy saving effect of a living filter appliance. Since only one floor is considered, the rest is modeled without zones. This makes IDA ICE treat the floor and ceiling of level seven as adiabatic and the energy usage of the rest of the building is neglected from the simulation [42].

![Figure 11: 3D View of the building and modeled floor.](image)
Location
The actual building is located in Umeå but the simulation location was set to Sundsvall due to an incomplete locations package for the IDA licence. The climate file holds statistics weather data which is used in the simulation. The simulation climate is set to Umeå, Sweden and the wind profile to urban.

Construction
Construction materials are left as default and assumed the same around the building envelope. This will not effect the comparison between two simulations of the same house and is elaborated further in the discussions chapter.

Schedule
Occupants, lighting and some equipment are programmed to be on a schedule according to the working hours and routines of the employees. Office areas are occupied during working hours 07.00-17.00 on weekdays but not during lunch and breaks. Lighting and equipment is on during working hours and a few percent are left on all the time. The lunch room is heavily occupied during work breaks and otherwise only occupied sporadically.

Infiltration
The infiltration of the simulated building have been measured at 50 Pa pressure difference to 0.364 l s$^{-1}$ m$^{-2}$ where the area mentioned is that of the building envelop external surface. This value is implemented to IDA by setting the air tightness to 0.225 and choosing wind driven flow in the bullet list.

Air Handling Unit
The AHU uses a VAV system regulated by the variation in CO$_2$ concentration and the air temperature in the room according to the Lindinvent valves used in the actual building. A minimum flow of 0.35 l s$^{-1}$ m$^{-2}$ floor area and 7 l/person is implemented according to the BBR minimum demands for offices. Thus there will be a basic ventilation which is always on. The flow will change according to the demands from CO$_2$ and temperature caused by the occupants schedule and the flow will be forced to increase when the CO$_2$ concentration reaches 800 ppm. In System Parameters the incoming air is set to have a CO$_2$ concentration of 450 ppm since the building is located in the center of the city, surrounded by traffic.

Zone Structure
The simulated floor is divided into five zones which are displayed in figure 12. The blue lines represent zone boundaries and also internal walls. The yellow liner represent internal openings. The properties of the five zones are as follows;
1. Contains offices, conference rooms, lavatories, staircases to adjacent floors as well as elevator and installations shafts. Common areas and hallways fill the space between rooms.

2. Lavatories, stores and hidden installations for the kitchen, no one occupies this space continuously.

3. Staircases to adjacent floors, a room for equipment such as printers and a small conference room. This zone has occupants sporadically in the conference room.

4. A coherent row of offices with one to four occupants per room.

5. Lunch room with coherent hallways. A small kitchen is placed on the wall bordering zone 2. Occupation is sporadic throughout the day and regular during lunch and coffee breaks. On the short wall bordering zone 4 the
living filters are located and this is where all objects associated with the modeling of the living filters are placed.

**Living Filters**
When implementing the living filters into IDA ICE the living filter was treated as the resultant of its physical parameters. The implemented living filters are considered to be three glass cabinets of the stand alone type, all with an air flow of 150 m$^3$/h per cabinet. The placement and number of filters modeled are according to a request from the tenant company in the modeled building, Rambøll.

- **Lighting**
  The powerful 6000 K LED lamps are modeled as one extra lamp of 30 W placed where the living filters are depicted in zone 5.

- **Humidification**
  This is a result of the watering systems spray-like character and byproducts from the photosynthesis. It is modeled as an addition of liquid water by an additional equipment. This requires energy to evaporate which is taken from the heat of the room. Thus the cooling effect described by equation 2.1.1 & 2.1.2 is accomplished.

- **CO$^2$**
  The reduction of CO$^2$ is accomplished with the inbuilt IDA function for CO$^2$ emissions from equipment. By giving the humidifier a negative value of CO$^2$ emissions it acts as a CO$^2$ sink. This effects the Air Handling Unit (AHU) forced vent operation in the zone by decreasing the time this function is required to uphold concentration values of less than 800 ppm CO$^2$.

- **Operational Power**
  Various components of the living filter require electrical energy to function and thus extra electrical consuming equipment is added in the zone to represent this need.

4.2 **Comsol Multiphysics Simulations**
The air flow in a room equipped with a living filter is simulated with *Comsol Multiphysics* to determine the expected ventilation efficiency and how the living filter affects the air flow in a room.
A 2D room of dimensions $8 \times 2.7$ meters is constructed in *Comsol Multiphysics* and a living filter stand alone product with dimensions $0.8 \times 1.73$ meters. The flow through the filter is set to $150 \text{ m}^3 \text{ h}^{-1}$ and a temperature decrease of $1.5^\circ C$ as the air passes the filter is implemented. The living filter is modeled as two connected blocks where the top is set as a volume flow sink and the bottom is set as a source of equal flow rate. The room acts as one volume force of air where on the left side a window and a radiator is located to generate some natural circulation. The window is a two pane glass window, with argon in between, generating an $U$-value of $2.9 \text{ W m}^{-1} \text{ K}^{-1}$ with an outside temperature of $0^\circ C$ and the radiator has a constant temperature of $45^\circ C$. To investigate the risk of short cut ventilation over the living filter three models were created, using different ventilation principles. In the first model the room had no other ventilation, in the second the room had a displacing ventilation and the third model simulated a room with ventilation according to the mixing principle. A vector function was used to illustrate the flow where direction is indicated by each arrow and the flow velocity is denoted by the arrows length.

**No External Ventilation**
The case with no external ventilation was simulated twice. First the living filter was placed by the right wall in the room, thus the air could only circulate on one side of the filter. This generates the ideal conditions for short cut ventilation to occur. Thereafter the filter was placed in the center of the room which yields one additional direction for the air to leave the filter and thus returns a higher ventilation efficiency.

**Displacement Ventilation Principle**
To model a ventilation system according to the displacement ventilation principle a large supply valve was placed on the floor near the left wall. The valve supplies air both to the left and right from relatively large areas to achieve a low flow velocity. The extract valve was placed in the ceiling above the living filter.

**Mixing Principle Ventilation**
An additional inlet valve is modeled in the ceiling, 1 meter from the left wall and an extract valve is put in the ceiling above the living filter, same as for the displacement simulation. The air flow is adapted to replicate a room ventilated according to the mixing principle.
5 Simulation Results

The results from the simulations with IDA ICE and *Comsol Multiphysics* are displayed in the respective sub chapters.

5.1 IDA ICE

Table 3 is the energy and power demand for the simulated floor during one year. This is not the real energy and power demand of the building but simply a reference for comparison. The fields highlighted by a red square are the most interesting to compare with a living filter application. In the reference simulation the energy demands of the living filters are zero, naturally. The *Grand total* on the bottom line is the total energy consumption during one year for the simulated floor, all energy species combined.

<table>
<thead>
<tr>
<th>Table 3: Simulation report of the modeled floor.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Delivered energy</strong></td>
</tr>
<tr>
<td><strong>kWh</strong></td>
</tr>
<tr>
<td>Lighting, facility</td>
</tr>
<tr>
<td>Electric cooling</td>
</tr>
<tr>
<td>HVAC aux</td>
</tr>
<tr>
<td><strong>Total, Facility electric</strong></td>
</tr>
<tr>
<td>Domestic hot water</td>
</tr>
<tr>
<td><strong>Total, Facility fuel</strong></td>
</tr>
<tr>
<td>District heating</td>
</tr>
<tr>
<td><strong>Total, Facility district</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
<tr>
<td>Equipment, tenant</td>
</tr>
<tr>
<td><strong>Total, Tenant electric</strong></td>
</tr>
<tr>
<td><strong>Living Filters consumption</strong></td>
</tr>
<tr>
<td><strong>Total, Living Filters</strong></td>
</tr>
<tr>
<td><strong>Grand total</strong></td>
</tr>
</tbody>
</table>

Table 4 is the result of a simulation identical to table 3 but with the properties of a living filter added. The highlighted red squares shows on what energy meters the living filters have had an impact. The energy usage from the components associated with the living filters are sorted out and displayed on a separate energy meter, denoted with *Living Filters consumption*. Despite this added electrical effect the *Grand total* energy demand is lower with living filters installed.
Table 4: Simulation report with a living filter implemented. The HVAC-post is the heating, ventilating and air conditioning system.

<table>
<thead>
<tr>
<th></th>
<th>Delivered energy</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kWh</td>
<td>kWh/m²</td>
</tr>
<tr>
<td>Lighting, facility</td>
<td>51307</td>
<td>34.2</td>
</tr>
<tr>
<td>Electric cooling</td>
<td>899</td>
<td>0.5</td>
</tr>
<tr>
<td>HVAC aux</td>
<td>11314</td>
<td>12.4</td>
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<tr>
<td>Total, Facility electric</td>
<td>43920</td>
<td>47.5</td>
</tr>
<tr>
<td>Domestic hot water</td>
<td>1465</td>
<td>1.6</td>
</tr>
<tr>
<td>Total, Facility fuel</td>
<td>1465</td>
<td>1.6</td>
</tr>
<tr>
<td>District heating</td>
<td>2023</td>
<td>2.2</td>
</tr>
<tr>
<td>Total, Facility district</td>
<td>2023</td>
<td>2.2</td>
</tr>
<tr>
<td>Total</td>
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<td>31.3</td>
</tr>
<tr>
<td>Equipment, tenant</td>
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<td>25.6</td>
</tr>
<tr>
<td>Total, Tenant electric</td>
<td>22478</td>
<td>25.6</td>
</tr>
<tr>
<td>Living filters consumption</td>
<td>641</td>
<td>0.9</td>
</tr>
<tr>
<td>Total, Living filters</td>
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<td>0.9</td>
</tr>
<tr>
<td>Grand total</td>
<td>73327</td>
<td>77.9</td>
</tr>
</tbody>
</table>

440 kWh and 0.5 kWh/m² are the absolute energy savings for the entire office floor during a one year. The peak power demand for the Electric cooling, HVAC- and district heating systems are also reduced.

5.2 Comsol Multiphysics

The Comsol Multiphysics simulation outputs are displayed as a view of the simulated room with arrows to illustrate the air flow. In figure 13 the primary flow is short cut as is to be expected when the room is long, the ceiling low while temperature difference and velocity of the supply stream is small compared to the steady state values of the room. This well illustrates a worst case scenario for a living filter cabinet.
Figure 13: Simulation without additional ventilation in a room. Worst case scenario for ventilation efficiency of a living filter.

When the living filter is placed more centrally in the room, as in figure 14 it is able to affect all the air in the room volume more effectively. It is only at the far right end of the room the air becomes noticeably stagnant.

Figure 14: Simulation without additional ventilation in a room. Placement of the living filter makes the air flow affect the entire room.

In figure 15 the flow looks much like the theoretical displacing flow in figure 8. However, the flow from the living filter takes a short route to the exit valve or back to the filter. The situation is not ideal and a consequence of the displacement valve supply stream and the living filter supply stream facing head to head causing a resulting upward flow.
Figure 15: Simulation of displacement ventilation combined with the living filter. Ventilation supply valve is located to the left on the floor and the extract valve is in the ceiling above the living filter.

Simulations of flow according to the mixing principle is shown in figure 16. The flow velocity from the supply valve is high enough to provide a well mixed air volume. The supply velocity from the living filter is so small in comparison the arrows next to the lower part of the filters are only hardly seen. In this situation the extract valve and the living filter effectively share the extract air stream giving the living filter ideal conditions to increase the ventilation efficiency described by equation 3.2.4 & 3.2.5.

Figure 16: Simulation with mixing ventilation combined with the living filter. Ventilation supply valve is located in the ceiling to the left and extract valve is located to the right, above the living filter.
6 Discussion

Installations of living filters can be found in a vast variety of buildings. This project has reviewed studies done at airports, companies and schools but also in a home, library and a church. Still questions remain, does it work? how reliable is it? and how do you design and size a system with a living filter ventilation?

The living filter is no new invention, however, the proven functionality of living filters is not a general accepted fact. A real case study with modern materials and methods can prove how a dynamic system application amplifies the air purifying properties of tropical plants, which are a static system by themselves.

IDA ICE

The constructed simulation models have both been built on a number of assumptions and simplifications. In IDA ICE all floors except the studied one have been left out. Since there is no living filter component in IDA ICE the resulting effect of a living filter had to be built using IDA standard components according to EQUA users guides [42]. The simulations show how energy can be saved by implementing living filters, however there is also a question of exergy. Powering the living filters require electric energy and reduces, among other factors, the buildings heating load by recirculating some of the ventilation air. If these were the only posts and electrical kWh input is 1:1 with reduced kWh heat the energy cost/saving would be zero but, if the building is not heated with electricity, exergy would be lost since electric energy contains more exergy than heat. The IDA ICE simulation results show how a buildings energy usage can be reduced with a living filter appliance although the economic savings through energy will not return the investment on stand alone living filter cabinets.

The placement location of the living filters in the IDA ICE simulations was mainly because my partnering company Ramböll wanted an investigation of how a living filter appliance would affect the energy usage and power demands in their new office floor and specifically by placing them in the lunch room. The occupation schedule, load and zone layout makes the lunch room far from an ideal location for the living filters if the aim is to save energy. However, when it comes to creating a high average air quality, I believe based on my studies, the lunch room is a very good placement for the living filter. To have the largest impact on the buildings energy consumption the simulated living filter or filters should be placed in a conference room which is often used by many people at the same time and where the ventilation is of VAV type regulated by CO\textsuperscript{2} concentration and temperature.

Comsol Multiphysics

The simulations with Comsol Multiphysics have also been largely simplified. Most important is the reduction from 3D to 2D which reduced the simulation time from days to hours. In the simulations with mixing and displacing ventilation the flow is set relatively low because fluid calculations and volume force both
severely affect the number of computations required during a simulation. Reduc-
ing the scale of the room is, realized in hindsight, a more efficient simplification
and also less affecting on the result. Another way to increase computational
power is to divide the the operations between the processors cores or to perform
the calculations on an external computer over a cloud service. Simulations of
displacing ventilation with a living filter indicates a high risk of short cutting
air flow over the living filter. This result is part because of the modeled layout
of the room and since the living filter also uses the displacement principle a
remodeling with different room layout might provide more general results. The
largest drawback with the Comsol Multiphysics simulations is the timeframe.
This project was not originally intended to contain any Comsol Multiphysics
simulation and this idea came up pretty late in the project but was interesting
enough to investigate. However, this caused the long simulation times to have
quite severe impact on the model construction and simulation results.

Research Review
All my findings and understanding of living filters comes from the review and
compilation of other scientists research. This poses a significant flaw in my
work since all studies design and execution has its drawbacks, mine is the sum
of all unaccounted errors in the works examined. This may, however, also pose
a strength since I have had the opportunity to filter out all results which have
seemed unreliable and all studies where the scientific method have had a signif-
icient flaw or bias. This project originally aimed to quantify the air purifying
properties of a living filter. However, an experimental design which would be
reproducible for any scientist, include all agents mentioned in chapter 2.2 and
span over enough time to give long term viable results proved to be too resource
demanding for this project.

Building regulations today are written in a very strict manner which not only
specifies good air quality but a minimum required air flow from outdoors and
that any re-circulation of air needs purification which must be tested for its
functionality on every installation. This is the major issue before living filters
can have an impact in general ventilation systems design. An acknowledgement
of sorts from the authorities constituting the building regulations. For this to
happen, there must come a sizing tool by which consultants can relate to when
designing and sizing a ventilation system.

Integrated Installations
The two reference installations described in chapter 2.5 are sites I have come
across and visited during this project, both being examples of functional install-
ations of living filters. The filter at Midlanda airport have been running since
1997 and according to the airports management and the living filters manufac-
turers, the air quality out from the filter have been tested several times dur-
ing these twenty years although only the first examination, [10], sponsored by
NUTEK, was ever published. This sort of installation where the living filter is
fully integrated with the buildings ventilation system gives the living filter more
power to directly affect both the indoor air quality and the energy usage of the building. It is also a more long term technical solution for the appliance of living plants to purify air. The future utilization of living filters and its appliance in building engineering will be an interesting development to follow.
7 Conclusions

Using living filters as a complement to conventional ventilation will increase the indoor air quality.

In combination with a $\text{CO}_2$ regulated VAV ventilation system a complement with a living filter will improve the energy performance of the AHU and decrease its peak power demand.

Swedish building regulations requires the functionality of every installation outside regulation norms to be verified.

Living filters may present an alternative ventilation solution to hospitals and similar environments where the demands for clean air are especially high.
8 Future work

Research
By scientifically determining how much CO$_2$, other gases, particles and water vapor the equivalent of one living filter absorbs or produces quantified in g/s, installations consultants will be able to project and size ventilation systems in which living filters are part.

Development
For consultants to direct certain installations, necessary projection tools must be provided. A magi-cad, or corresponding, plug-in which provides sufficient data to dimension a ventilation system equipped with living filters must be developed.

Widening the Scope
This project has focused mainly on the air purifying properties of plants incorporated into living filters but this is only the tip of an iceberg. What if internal walls could be covered with plants where air is purified and eatable fruit and vegetables grow? The utilization of plants indoors has a vast and yet growing potential of increasing importance as people in general spend all the more time indoors.
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Appendix

Figure A: Mollier diagram for humid air.