User-Centric Redesign of Skid-Based Ventilation Systems for Energy-Efficient Building Renovations

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0.1 | Acknowledgements

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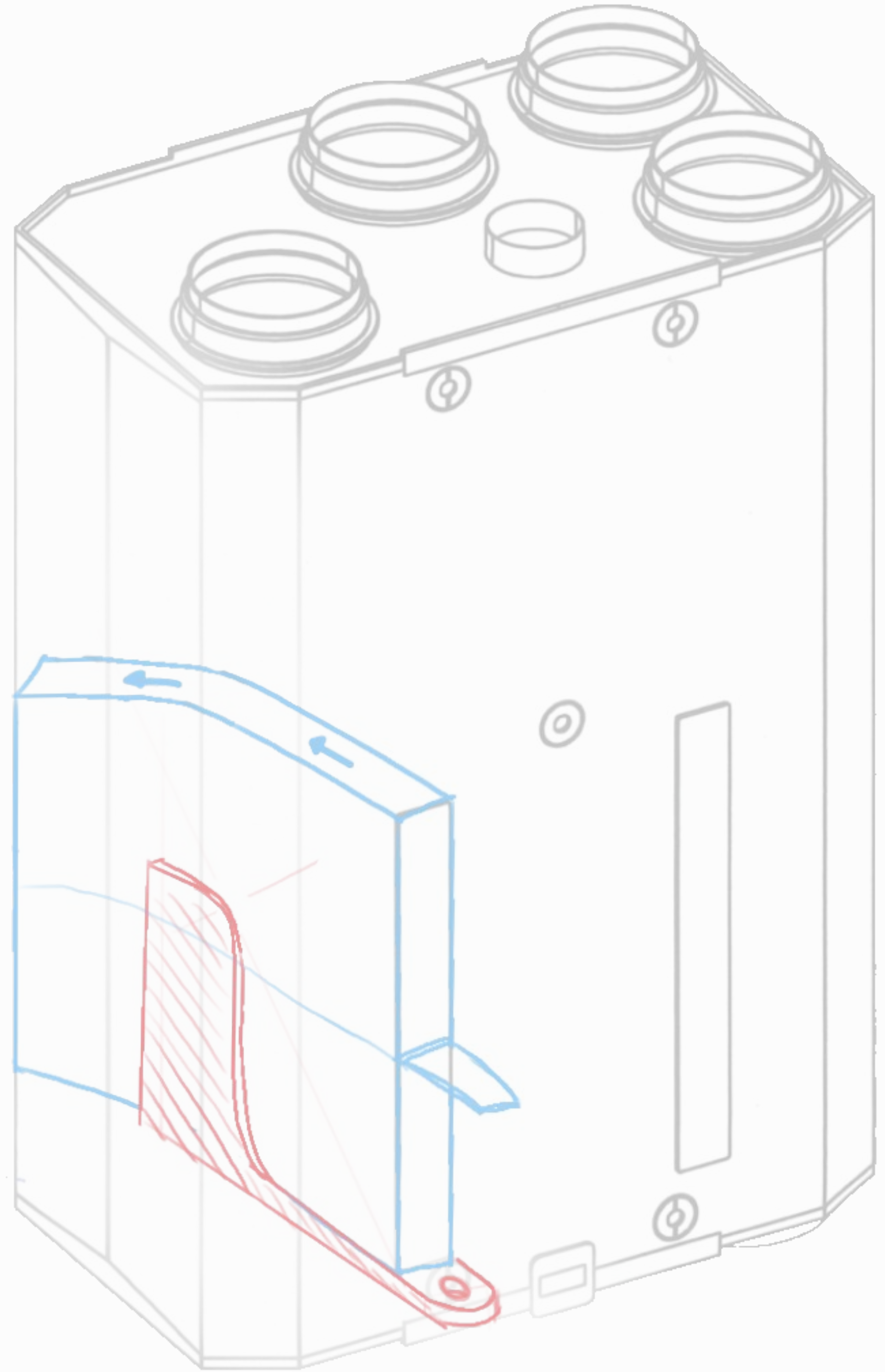
0.2 | Executive summary

This thesis proposes ten practical principle solutions to manufactures of Mechanical Ventilation with Heat Recovery (MVHR) systems to make their designs more user-friendly. Through detailed exploration and prototyping, the thesis aims to provide feasible means to improve the interaction of residents with these energy efficient systems in their homes, thus enhancing their quality of life.



Most residential buildings in the Netherlands are energy inefficient, with many still relying on fossil fuels as their primary heat sources. As Dutch society transitions toward energy neutrality, sophisticated technologies are being implemented to enhance the energy efficiency of residences. Despite these advancements, residents often struggle to use these systems to their full potential.

This project investigates the underlying reasons for this issue through a comprehensive approach involving research, observation, interviews, prototyping, and user testing. The insights gained are then used to formulate actionable recommendations for equipment manufacturers aimed at redesigning ventilation systems to improve residents' quality of life.

Initially, the project focused on interactions with skid systems as a whole. However, over time, it evolved to concentrate specifically on maintenance interactions with Mechanical Ventilation (MV) units within the context of skid systems.

The outcome of this thesis is a set of ten practical recommendations for equipment manufacturers of ventilation systems on how to redesign them, along with an identification of significant information gaps that need to be addressed.

1. Introduction

Resident-technology interaction is often a neglected aspect in the designing energy-efficient homes. This chapter outlines the graduation project, emphasizing the need for improved housing systems and detailing the project's scope and design approach.

1.1 | Problem Statement

1.1.1 Unsustainable Energy Consumption

Residential buildings in the Netherlands account for 30% of total national energy consumption (Ortiz et al., 2020). Of this, a large portion is residential heating. In older houses with poor insulation, most of the heat generated by the gas boilers is lost to the atmosphere.

To combat this unsustainable energy use and to reduce the reliance on fossil fuels, a combination of building-related energy efficiency measures are implemented. For instance, insulation, mechanical ventilation, renewable energy systems such as heat pumps, solar panels, district heating, and their related distribution systems, e.g., low-temperature heating and smart grids, are utilized (Ortiz et al., 2020).

1.1.2 Energy transition

The European Union (EU) has set goals to achieve Net Zero Emissions by 2050 (European Commission, n.d.), a goal that presents significant challenges due to various factors.

One major obstacle is that construction regulations restrict the number of new buildings that can be built, which is much lower than the number of existing inefficient structures. Additionally, certain older buildings may be protected from demolition, necessitating energy transition solutions that are suitable for renovation rather than new construction.

Low-Temperature (LT) systems, designed to be more energy-efficient, are more complex than traditional gas-heating systems. The high calorific value of fossil fuels allows gas boilers to heat residences quickly, while LT systems provide heat more gradually, making them less appealing for widespread adoption (van Beek et al., 2023).

1.1.3 The neglected stakeholder

Housing in the Netherlands involves a complex network of stakeholders, where decisions on greenlighting projects are influenced by factors such as costs, available subsidies, regulatory compliance, and the choice of suitable technologies. However, in this intricate process, the residents—who are the most directly impacted by these systems—often have the least influence, especially renters.

Highly efficient systems are designed with the assumption that they will be used as intended. This presumes that residents are both knowledgeable and motivated to understand and manage these systems effectively.

However, research indicates that energy consumption between two identical zero-energy (ZE) apartments can vary by up to a factor of three due to differences in occupant behavior (Pretlove & Kade, 2016). This suggests that the actual efficiency of ZE systems is strongly influenced by how residents interact with them.

The interaction between residents and the ZE systems in their homes is often a non-designed interaction, leading to a gap between expected and actual performance. This not only undermines the intended efficiency of the systems but also adversely affects the quality of life for residents.

The aim of the project is the improve the quality of life of residents of Zero-Energy housing by elevating the user-technology interaction.

Key Takeaways

- Residential heating is a large cause of national energy consumption.
- Residents of energy efficient homes often do not use the systems as intended.
- This user-technology dissonance leads to reduced quality of life for residents.

[1] Boess, S. (2022). https://doi.org/10.17645/up.v7i2.5107

1.2 | Scope

The project proposes principle solutions to manufacturers of MHVR systems, targeting key gaps in user-system interactions and providing strategies to address these issues.

This means that instead of proposing a final detailed concept, I present a set of principles that manufacturers can apply to resolve various challenges, supported by a physical prototype that is validated by users and domain experts.

There are many different kinds of Energy Efficient housing systems implemented in the Netherlands. The scope of this project is limited to skid-type systems, particularly within renovation contexts. This focus is due to the supervisory team's familiarity with the system and the availability of relevant resources.

In line with my interests, skills, and learning objectives, the project emphasizes the technical feasibility and manufacturability of the proposed solutions as part of a product-service system. I achieved this through a combination of observations, interviews, research and prototyping. Aspects such as UI and automation are not focused on.

1.2.1 Final Deliverables

- Recommendations for manufacturers to enhance system usability, along with strategies for implementing proposed solutions.
- Analysis of root causes for user-technology dissonance
- Concepts for user-friendly redesigns of ventilation system
- Proof of principle prototype
- Validation of proposed solutions with residents and domain experts

The main focus of the graduation project lies with the proposal of feasible and viable principle solutions to manufacturers for the user-centric redesign of energy efficient systems.

Key Takeaways

- This project offers principle solutions to MVHR system manufacturers as opposed to a detailed design
- The scope is limited to skid-type systems in renovation contexts
- Technical feasibility and implementation of proposed solutions is focused upon.

1.3 | Project approach

The opportunity for this thesis work arose through the IEBB Project, a multi-year, multi-stakeholder initiative focused on developing affordable and user-friendly renovation concepts for residential buildings (Integrale energietransitie bestaande bouw, n.d.). The initial brief provided by my thesis chair, a researcher involved in the IEBB project, was to integrate a resident-oriented perspective into energy-saving designs for homes.

Given the complexity and scope of the project, I started with an analysis phase to familiarize myself with the domain and stakeholders. This orientation phase led to the selection of a target audience. Following this, I explored various solution spaces, refined concepts, and evaluated them with users and experts.

The design process was structured into four distinct phases as shown in Fig 1, each iterative and involving frequent revisions. The process required numerous assumptions and educated guesses, with design directions adjusted as assumptions were validated or invalidated.

This four-phase approach parallels the double diamond design process, with each phase reflecting the divergence and convergence characteristic of the model.

Fig. 1: 4 Phase design process

Key Takeaways

- A four-phase iterative design process was used, involving adjustments based on validated assumptions.
- The design exploration consists of phases of exploration and phases of synthesis

Chapter 1: Conclusion

With the scope and design approach defined, the next step is to begin research to familiarise myself with the domain of the project.

2. Context

This chapter delves into the project's context, drawing from research and expert discussions. It provides an overview of housing in the Netherlands, HVAC systems, skids, and the key stakeholders involved. The chapter concludes by identifying the chosen target group.

2.1 | Housing in the Netherlands

The phase begins with some background research about types of housing in the Netherlands. Some of the popular types of housing are mentioned below.

A porch house is often found in urban areas. The word "porch" refers to a common hallway that provides access to multiple units in a building. Each home usually has its own front door that opens onto the porch, allowing residents to enter their home without going through a communal hallway (Huurstunt, n.d.-a).

A corridor flat consists of several individual apartments that are accessible via a common hallway or corridor. Each flat has its own front door that opens onto this shared hallway, which has elevator or stair access (Huurstunt, n.d.-b).

A gallery flat is an apartment building characterized by a long, open corridor that extends over several floors and provides access to the various apartments. Gallery flats are often found in urban areas and are built to make efficient use of available space (Huurstunt, n.d.-c).

The construction type influences which energy saving technologies can be implemented. Additionally, certain types of flats often cater to specific demographics. For instance, houses from the 1950s and 1960s frequently house elderly residents who tend to have higher expectations for thermal comfort (Wahi, personal communication, April 2024). Similarly, social housing projects have different needs and priorities in terms of housing solutions

Fig. 2: Portiekwoning (Porch House)

Fig. 3: Corridorflat (Corridor Apartment)

Fig. 4: Galerijflat (Gallery flat)

Key takeaways

- Porch houses, corridor flats, and gallery flats are popular types of housing.
- Housing type influences the kinds of energy saving technologies that can be implemented.
- The demographic of the residents affects their needs and requirements as well.

Fig. 5: Facade of a building extended to improve insulation

2.2 | Energy Efficient Renovations

The renovation process for improving energy efficiency can differ from one house to another, but the core principles of heat retention, efficient heating, and ventilation are universally applicable. The following section details these principles and provides an overview of specific energy-efficient systems.

2.2.1 Insulation

The first and most important step in conserving energy is to prevent heat loss to the environment. Heat typically escapes through walls, windows, and open ventilation grills. Radiators are sometimes placed directly next to windows which leads to further heat loss.

To retain heat within the house, facades are thickened with insulating materials, reducing the amount of heat that escapes through the walls. Windows are often glazed, and airflow is sealed off to further reduce heat loss.

Fig. 5 shows an example of a building facade extended to improve insulation.

2.2.2 Efficient Heating

Gas boilers are not legal as primary means of residential heating for newly built houses (Wahi, personal communication, April 2024). They may still be used as auxillary heaters in hybrid systems, but the bulk of residential heating is done by more energy efficient systems, which are briefly explained in the following sections.

Heat pumps

A heat pump extracts heat from a source, such as the surrounding air, geothermal energy stored in the ground, or nearby sources of water or waste heat from a factory. It then amplifies and transfers the heat to where it is needed (The Future Of Heat Pumps – Analysis - IEA, 2022). Heat pumps are much more efficient than boilers or electric heaters, and are 3-5 times more efficient than gas boilers.

The heat pump itself consists of a compressor, which moves a refrigerant through a refrigeration cycle, and a heat exchanger, which extracts heat from the source. The heat is then passed on to a heat sink through another heat exchanger (The Future Of Heat Pumps – Analysis - IEA, 2022).

This heat is then delivered through systems such as radiators or under-floor heating, which are explained further on.

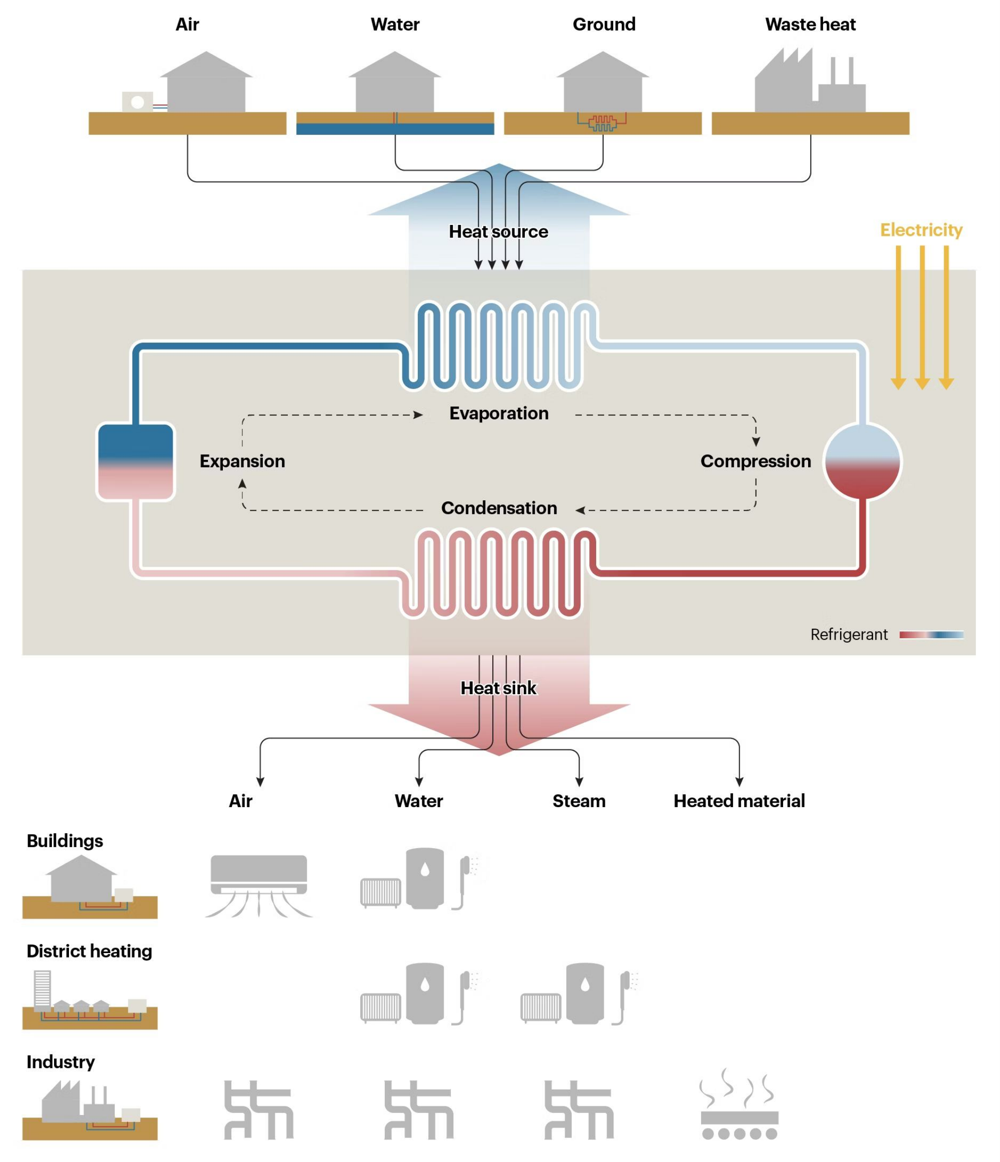


Fig. 6: Working principle of a heat pump [1]

District Heating

District heating involves generating heat in a centralized location and then distributing it to residences, businesses and industry in a local area (District Heating - Energy System - IEA, z.d.). District heating in the Netherlands is provided by the Netherlands, and requires a distribution set.

In a similar fashion, an entire building can be heated using centralized high-capacity heat pumps that distribute heat through radiators. This system, known as block heating, operates on a smaller scale compared to district heating.

Fig 1: Extended facade of a building

Infrared Heating

Infrared heating utilizes heating panels to emit infrared radiation, providing an efficient method of warming a space with the potential for lower energy bills. However, it requires a panel in every room, leading to high upfront costs (Duchene, 2024).

This system is less effective in rooms with high ceilings and necessitates thorough insulation to function optimally. Additionally, infrared heating can be rendered ineffective if furniture obstructs the infrared rays. On colder days, supplementary heating systems might still be needed to maintain comfort (Duchene, 2024).

Underfloor heating

Underfloor heating is significantly more efficient than traditional radiators but comes with a higher cost and requires major renovations. This system raises the floor level noticeably. Wall heating operates on the same principle as underfloor heating but is less commonly used. Generally, underfloor heating is preferred for new constructions rather than for renovations (Wahi, personal communication, April 2024).

Fig. 7: Infrared heating panel

Fig. 8: Underfloor heating

Fig 1: Extended facade of a building

Solar Boilers

Solar boilers address the limitation of heat pumps, which cannot heat water quickly enough for showers and kitchen use. They are a viable option for houses with flat or tilted roofs. Photovoltaic panels are effective even if there is a difference of up to five stories between the roof and the residence. Subsidies are available for solar technology. Solar boilers can also be gas or electric, but they require an upfront investment and the panels need regular cleaning.

Fig. 9: Solar Boiler

Buffer tanks

Buffer tanks act as an intermediary between heat pumps and hot water systems by storing heat in water, which is then used for both heating and hot water. They can impact resident comfort because, unlike gas boilers, their capacity for providing hot water is limited each day. For instance, they might only support two showers per day.

Fig. 10: Buffer tank

Key Takeaways

- A heatpump is a very efficient and versatile LT system that is widely used.
- Multiple apartments can be provided heat through centralised district heating or block heating systems
- Infrared heating and underfloor heating are unpopular due to high initial investment and limitations of use.
- Unlike gas boilers, buffer tanks have limited capacity for hot water.

2.2.3 Mechanical Ventilation

Completely insulating homes to be airtight causes complications. Since natural airflow is no longer possible, a mechanical ventilation system must be installed. An airtight home is also at a higher risk of dampness and mold formation.

Typically, most mechanical ventilation systems in energy efficient houses have heat recovery system. These MVHR units are designed to run 24/7, extracting damp and stale air and replacing it with fresh air from the outside.

As the stale air is extracted, it passes through a heat exchanger where it transfers its heat to the incoming fresh air that is circulated back into the building. These units are designed to be unobtrusive and to draw minimal power (Ventilation Megastore, 2023).

Use and Maintenance

- MVHR systems need to be used and properly maintained.
- System takes care of ventilation. If windows are opened for air, causes heat loss.
- System is designed to run continuously. In case of shutdown, can cause mold growth, and health issues.
- Filters need to be cleaned and replaced regularly. Failure to do so causes health issues, increased noise, power draw, fan strain, etc.

Fig. 11: MVHR Illustration (Ventilation Megastore, 2023)

Fig. 12: Heat Exchanger of an MVHR unit of the Brink brand, seen at an observation visit.

Key Takeaways

- MVHR systems are used to circulate clean air through the house
- The system is complicated and requires proper use and maintenance to be effective
- Improper use could lead to increased energy usage and health complications for residents.

2.3 | Skid Systems

The term "skid" originates from factories, where multiple units of machinery are grouped in a single frame. In the context of housing, a skid houses major HVAC elements.

Fig. 14 shows the installation of an internal skid as implemented by Bosch Nefit in a redevelopment project in 220 homes in Nijmegen. The skids in this project were pre-fabricated at factories and transported to the construction site. There, they were lowered into the building via cranes, and the roof was then covered up.

This subsection presents the information known about the skid before selecting the target audience for the project. I chose the skids at the Nijmegen project as a baseline for analysis based on publicly available data and discussions with a project manager that executed a similar project *[source: eric mmid]*. As such, the information contains some amount of speculation.

Fig. 13: Modular process skid in a factory (Wikipedia contributors, 2023)

Fig. 14: Example skid, Bosch Nefit, Nijmegen (Bosch, 2023)

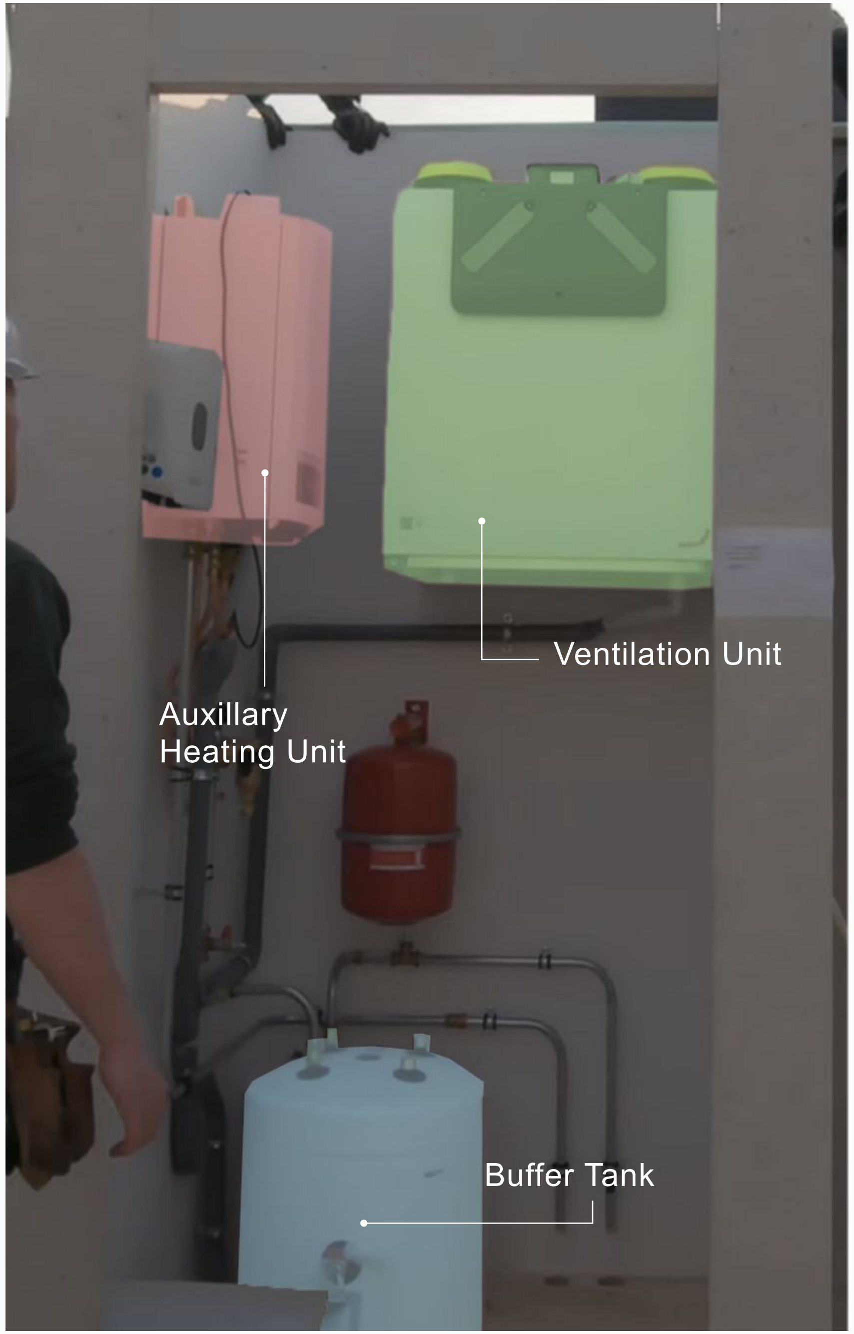


Fig. 15: Skid construction, Bosch Nefit, Nijmegen

2.3.1 Morphology of a skid

The figure shows the internal construction of the Bosch Nefit skid *[source]*. Skids of any type will typically contain some combination of a system for residential heating, heating or storing hot water, and a ventilation system.

The primary heating device is typically a heat pump. An air-to-air or air-to-water heat pump requires an additional outdoor unit. This can make it tricky to implement, especially in stacked apartments. The noise generated by these fans is an additional concern. Ground-to-water heat pumps make no noise and are easier to maintain, but require high investment and suitable conditions to install.

The apartments at Nijmegen are likely connected to block heating system in the building, as evidenced by the lack of a heat pump in the skid. If the skid were to be connected to district heating, it would require a distribution set, which is not present either.

An auxiliary electric boiler is seen in the skid, which is used to assist the primary heating system during days of extreme cold in winters. This is because the houses use solar boilers for hot water, and it is efficient to use the energy from the solar panels on the roof for auxiliary heating. Without a solar panel setup, an auxiliary gas boiler would be preferred (hybrid system).

The skid also has a buffer tank to store hot water, located at the bottom of the skid, with an expansion vessel for safety. And lastly an MVHR system for ventilation.

Fig. 16: Individual skid components (Bosch, 2023)

2.3.2 Benefits

Skids are versatile and can vary in implementation according to requirements. The core benefit of skids is the simplicity of grouping HVAC systems together.

Skids can be prefabricated to reduce installation time and skill required, which could save skilled labour costs for the project. This is especially beneficial in the Netherlands due to the scarcity of skilled workers. Skids also standardise available systems, making them more predictable and easier to maintain.

From a renovation standpoint, external skids can be installed on separately constructed facades, or placed on the ground. This makes it so that the house itself does not have the bear the load of these new systems, which is particularly useful for renovations of older houses.

Internal skids require lesser insulation and shielding, and are easer to accept. Since conceptually skids are essentially just frames, skid-based solutions are compatible with most HVAC solutions.

2.3.3 Drawbacks

While skids are efficient from an engineering standpoint, users can find the skid an alien and confusing environment. It can also cause great physical and cognitive strain to interact with components within the skid. Research from Boess (2022) shows these issues in the Fig. 17.

Fig. 17: Drawbacks of skid systems as experienced by the user

Key Takeaways

- A skid is a unit within which all HVAC related components are compactly placed
- Skids are popular due to their simplicity of construction and versatility, especially for renovation projects.
- Residents often face physical and cognitive strain when interacting with skids

2.4 | Stakeholders in the housing sector

A redevelopment project involves multiple stakeholders (Fig.1) with their own agendas. Government regulations must be adhered to. The Government also issue permits, provide subsidies for certain technologies like solar heating *[source]*, or services like district heating *[source]* if available.

An architectural firm designs the neighbourhood. A technical consultancy determines the heating, insulation, ventilation, and other requirements. They also ensure technical compliance. There can also be other parties such as non-profit consultancies that play an advisory role, such as when determining applicable subsidies.

A general course of action is decided by the housing corporation, which finances the project, and a construction company which then also executes the building of the renovation project, often in consultation with the chain of construction. This renovation consortium, comprised of the housing corporation, construction company and consultants buys HVAC systems to integrate into the building from equipment manufacturers.

An installation company does the actual on-site installation, and a service crew handles maintenance. These are usually third parties. Maintenance issues can be escalated to construction companies and equipment manufacturers.

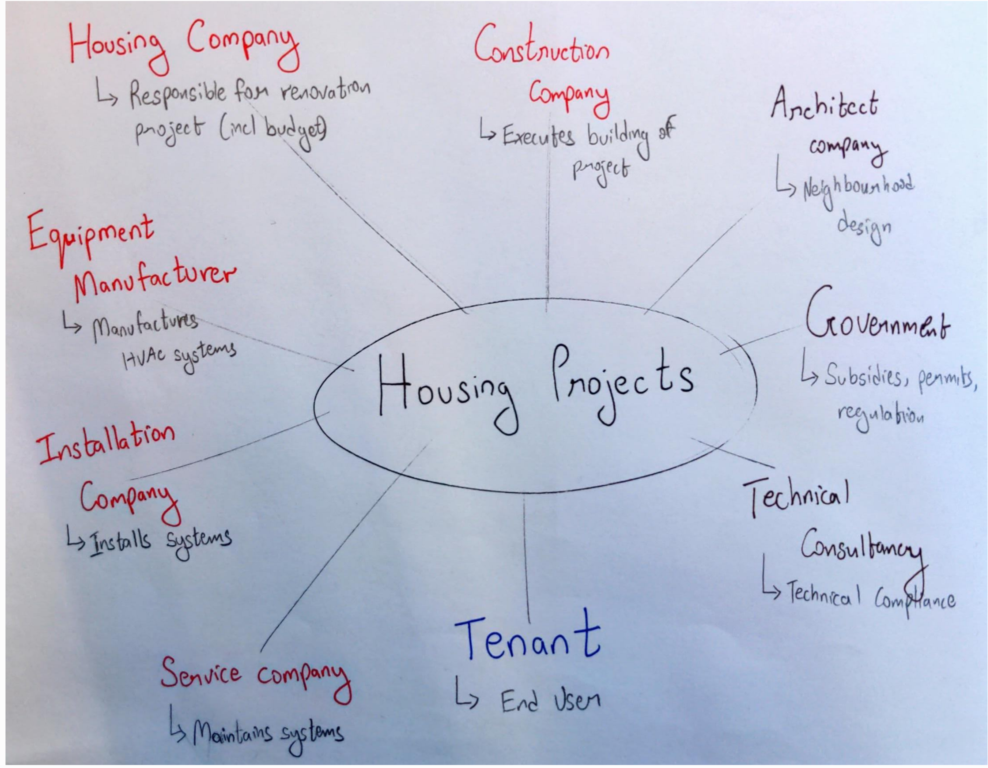


Fig. 18: Stakeholder map

Fig. 19: HVAC equipment manufacturers

Boess, (2022) and van Beek et al., (2023) analysed that residents as end-users are often neglected in this process. They have insufficient knowledge of systems, which can be hard to intuit during the complex design and renovation process. Maintenance may require too much cognitive and physical effort of them. As a result, improper use and upkeep may cause discomfort, health issues and reduced energy efficiency.

With an understanding of the domain and stakeholders, the next subsection discusses the determination of the target audience.

Key Takeaways

- There are multiple stakeholders in the housing sector, of which the resident is the most neglected.
- A focus group for the design has to be chosen before further analysis can be made.

2.5 | Focus group: Social Housing

It was necessary to narrow the scope of the project further and decide what my target audience would be. I chose my focus group as social housing projects.

Social housing in the Netherlands is government or non-profit housing offered at below-market rates to low- and middle-income households for affordable and stable living. Approximately 30% of the housing stock in the Netherlands is comprised of social housing. (Voorbeeldwoningen Bestaande Bouw, z.d.)

These residences have limited budgets, simple construction, and sizes ranging from 60-110sq.m. (Voorbeeldwoningen Bestaande Bouw, z.d.). They comprise of both single-family houses and stacked apartments. Units within the same complex are usually standardised. Social housing tends to comprise of older, energy inefficient buildings that are in need of renovation.

Specifically, stacked apartments within social housing align most with the skids' strengths of prefabrication, cost effectivity, and renovation. The economic requirements for skids limits the possible variance.

Additionally, most residents of social housing tend to be renters, who have lesser tendency to be actively involved in the maintenance of their home as opposed to house owners (van der Voort, personal communication, May 2024) which creates an interesting challenge.

A redesign of skid-based systems for social housing presents an opportunity to make the greatest impact, limits variance, and the large number of residents in a housing project makes it viable to implement changes.

Key Takeaways

- Social housing is a large sector of housing in the Netherlands with limited budgets and fixed apartment sizes that reduces overall variance.
- Residents of rented social housing are less likely to be involved in maintenance of their homes.
- This sector is chosen as the focus area due to having the greatest potential for impact.

Chapter 2: Conclusion

This section has presented the key background elements of the project. Stacked apartments in rented social housing is the optimal focus group for skids. With this, the next step is to learn more about this chosen target audience.

3. Observations and Interviews

This chapter covers two observation visits where I examined the skid systems firsthand, along with their interactions with users. It presents insights gained from these visits, focusing on each relevant aspect of the chosen focus group.

3.1 | Observation Visits

Through stakeholder contacts, I gained access to two recently executed energy renovations. The first was a pilot apartment, which, although not currently inhabited, had been trial used by many residents over a two-year period.

Baudouin Knaapen, a consultant from Wooninfo.nl—a government-funded non-profit that provides advice on renting, buying, and energy—guided me through this apartment. He shared his experiences of working with the project answered any questions I had.

The second visit was to a housing block renovated six years ago. During this visit, I had the opportunity to tour two apartments, speak directly with the residents, and observe their interactions with the systems in their homes.

My thesis chair, Stella Boess, accompanied me. She has been involved with the IEBB projects related to this housing block for several years. Boess also answered many of my questions about the housing complex.

I also evaluated potential interactions between residents and their systems that I could not observe directly, drawing conclusions based on these assessments.

Fig. 20: Visit 1, Demo apartment interior, Reigersbos

Fig. 21: Visit 2, Housing complex with skids, Vlaardingen

3.1.1 Reigersbos demo apartment

This social housing complex, originally constructed in the 1980s, has undergone some energy-saving upgrades, such as installing double-glazed windows and refurbishing the facades. However, most apartments are still heated by gas boilers that have exhaust vents running through the facade (Knaapen, personal communication, May 2024).

Gas heating is no longer allowed as a primary source of residential heating for new buildings, but existing buildings can continue using these systems until their permits expire. For the Reigersbos complex, this permit is valid until around 2030.

As a result, major renovations are required. Wooninfo is supporting the social housing corporation with this renovation project by advising on decision-making, securing subsidies, and addressing other housing-related issues.

The apartment unit I visited was an unoccupied demo unit designed to test energy-efficient systems. This apartment featured an air-to-water heat pump, but the primary focus of my visit was the mechanical ventilation system, which was most relevant to my research.

Although this unit did not include a skid, I still gained valuable insights into HVAC systems. Knaapen also provided perspectives on the challenges and considerations faced by social housing corporations undertaking similar renovation projects.

Fig. 22: 3 storey housing complex, Reigersbos

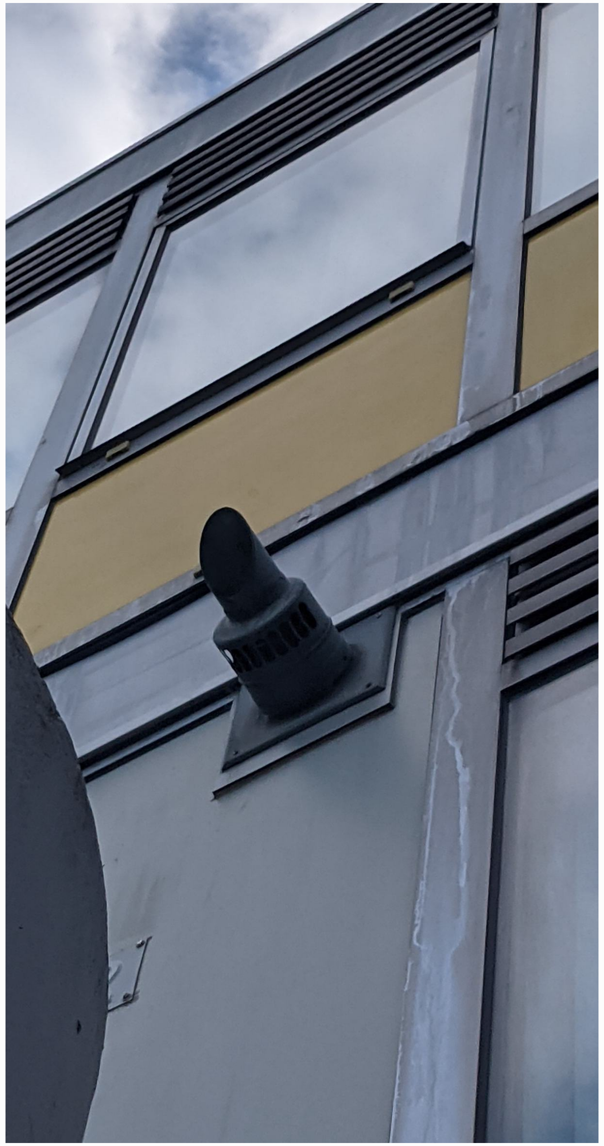


Fig. 23: Vent through facade

3.1.2 Vlaardingen Apartments

The social housing complex in Vlaardingen features three-story apartments, each equipped with an external skid. On the ground floor, the skid includes a ground-to-water heat pump that supplies heating to all three floors. Each floor is outfitted with its own ventilation system and a water boiler connected to solar panels on the roof.

The skid on the middle floor houses a buffer vessel for storing water and an expansion vessel for safety. Because the buffer vessel is a heavy, pressurized component, it is generally preferable to position it as close to the ground as possible. However, it was likely located at the second floor due to the ground-to-water heat pump. Consequently, the skid on the top floor remains relatively empty.

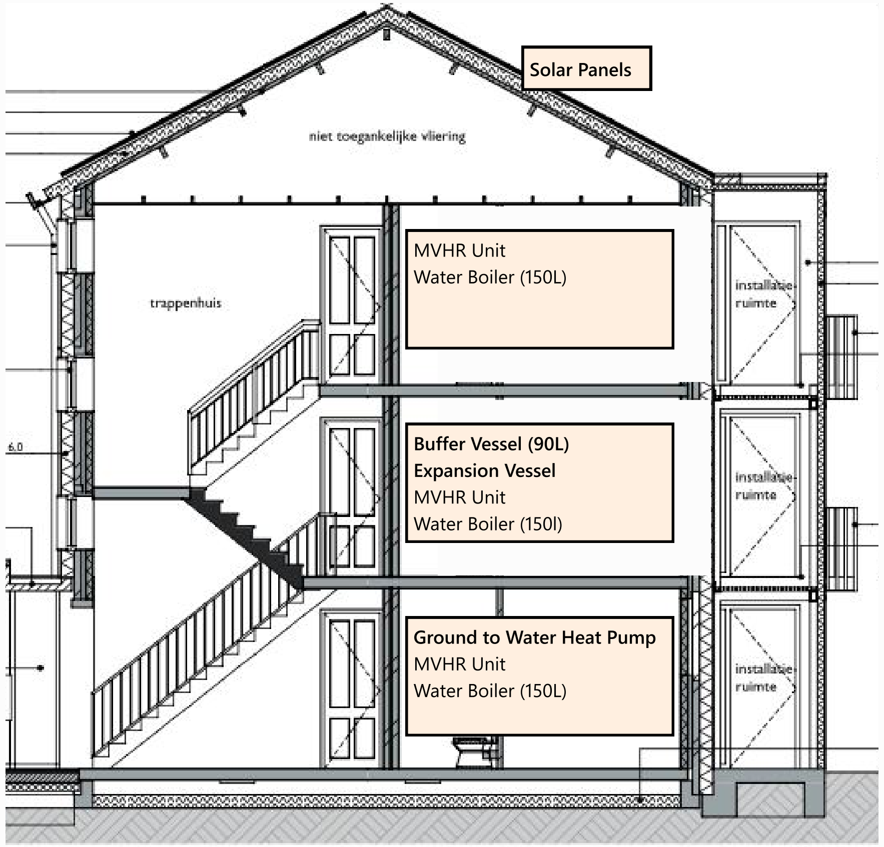


Fig. 24: Annotated Schematics for 3-storeyed Vlaardingen Apartments

I had the opportunity to observe the skid and its components firsthand and to interview two residents from the bottom two floors. To facilitate this, I prepared an interview guide focusing on user attitudes, knowledge about HVAC systems, and general perspectives.

Boess was instrumental in translating between English and Dutch, as the residents were fluent in Dutch but had limited English proficiency. The insights gained from these observations and interviews are detailed in the following section.

Key Takeaways

- Two apartment complexes were observed.
- The first complex at Reigersbos did not have a skid, but did have a mechanical ventilation system.
- The second complex at Vlaardingen had external skids. Two residents were interviewed.

3.2 | Interactions of Residents with Systems

Interviews with two residents (referred to as Resident A and Resident B) revealed several significant pain points. Unlike residents of private housing, those in social housing have limited control over the configuration or arrangement of their HVAC systems.

Additionally, residents had less understanding of their home systems than anticipated. Maintenance was generally handled by the housing corporation and third-party service crews, leaving residents confused about the systems, particularly in the context of the skid. Detailed observations of these issues are discussed further in the following section.

3.3.1 Ventilation systems

The Reigersbos unit had a simple mechanical ventilation. The system could be accessed by removing the unit cover, but since the control panel was on the cover, it had to stay connected to the main system via a cord. This made the cover difficult to handle. The filter lacked any gripping surfaces and had to be grabbed from one of the pleats, making it feel flimsy.

The button on the control panel was narrow and difficult to actuate, requiring a lot of force. The system was unintuitive, and was difficult to tell if it was responding as intended. After repeated attempts to switch power modes, my thumb felt sore.

I also noticed certain apartments had their inlet vents for gas heating obstructed by anti-roost pigeon spikes. It is common for residents to unknowingly obstruct inlet or exhaust vents *[pc: Boess, Knaapen]* as they do not understand the relevance of these systems. Sometimes, residents have also been known to seal off vents to prevent perceived heat loss.

Lack of transparency of the system, difficulty of actuation, and inconvenience of maintenance are issues residents may face. Since the Reigersbos system is quite different from the skid systems, I chose to focus on Vlaardingen more.

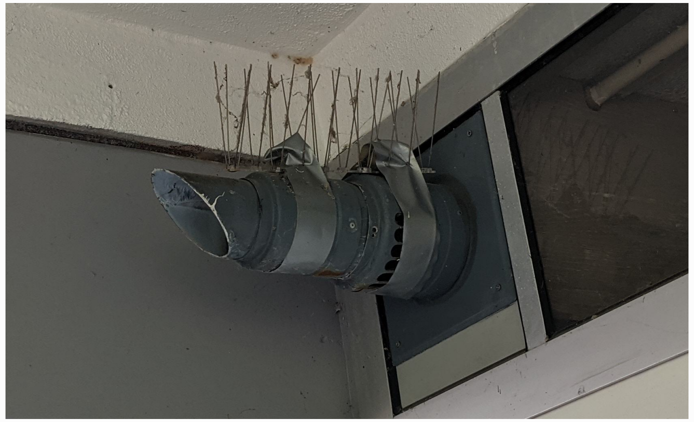


Fig. 25: Inlet vent for gas heated residence obstructed by anti-roost spikes.

Fig. 26: MV unit, Reigersbos

Fig. 27: MV unit with outer cover removed

Fig. 28: MV unit control scheme, Reigersbos

A MVHR unit in an apartment in Vlaardingen had three power settings, and an additional high power exhaust setting with a 10 minute timer *[fig.xx]*. However, these functions are not clearly stated. Resident B has the system always set at 2, and uses the timer function for showers.

Resident A however, does not use the timer, instead manually switching to 3 and back to 2 after the shower. The ventilation system in this house was noticeably noisy. Due to this, the resident sets the unit to 1 when sleeping. This is not ideal, as the MVHR unit is designed to be set at 1 when there no occupants in the house.

The interface for changing the settings is not too clear. The main feedback when changing the filter modes is the change in the noise of the system. I found it difficult to ascertain what power mode the unit was on by visual observation.

Neither resident had particularly motivated choices for their power settings. Mostly stuck with what they were told by professionals. The manual makes mention of these settings, but they are not easily accessible.

Commonly used inlet and outlet vents are difficult to tell apart. They can be inconveniently placed as seen in Fig X, where the vent is positioned above a cabinet. A vent such as this could be easily obstructed if the resident were to store things atop the cabinet. These vents are often dirty. They are difficult to access, and if they are cleaned, it is not possible to tell if they flow rate has been altered in the process.

Fig. 30: Exhaust vent above kitchen cabinet

Fig. 29: MV unit control scheme, Vlaardingen

Fig. 31: Inlet vent to skid very dusty

The ventilation unit must be depowered in case of emergencies such as a fire in the neigbourhood, or to perform a system reset. Particularly, power to the MVHR system is recommended to be cut off while cleaning or replacing the filters.

This is typically achieved by pulling the standard Dutch 3-pin plug. Electrical sockets in rooms are typically placed close to the ground. In skids, the socket position is likely determined by packaging or wiring constraints. In both cases, the plug point is difficult to access. It was difficult to even identify the correct plug in the skid amongst the tangle of other technologies.

This plug requires large amounts of force to disengage. The position of the socket, especially within skids requires users to apply this force in an awkward angle in a contorted body position. Since the angle of force application is not perpendicular to the wall, it requires an even greater amount of force to disengage.

In the section for replacing the filters, the manual for the Itho HRU 300 MVHR unit instructs to “remove the plug from the wall socket or de-energize the ventilation unit”. This implies there is an alternative method to depower the machine aside from pulling the plug. However, the manual makes no further clarification about this.

Fig. 32: Plug position at the bottom of the floor, MV unit

Fig. 33: Plug location, external skid

The filters in the MVHR system often go over a year without being cleaned or replaced. This is mostly handled by maintenance crews, and occassionally by residents.

Accessing the filters in the unit was difficult; while the cover was hard to remove, the filters themselves came out easily but were extremely difficult to insert back in. The filters were flimsy and bent easily, making them hard to control, which I expect would be a major problem while cleaning. This particular skid design complicated access further, as one of the filters was obstructed by the skid itself.

Although residents had been given instructions on the procedure during a previous project, they still struggled to remember it. There was a significant information gap. Residents lacked knowledge about the filters and the cleaning process, and even I found the system unintuitive.

Although the filters could be cleaned by vacuuming, this was not being done at all.

Fig. 34: MVHR Unit placement in skid

Fig. 35: Inconvenient to change filters of MVHR unit

Key Takeaways

- The ventilation system is complex and unintuitive.
- Minor non-designed interactions such as pulling the power cord cause great physical strain
- The MVHR system gets harder to interact with when it is within the skid.

3.2.2 Heating

The Vlardingen apartments make use of centralised heating systems that lack control for individual rooms. This can be inconvenient, since all rooms are not usually preferred at the same temperatures. For instance, bedrooms are typically required to be cooler than the general house temperature for ideal thermal comfort. The heating system is not transparent. It is difficult to know if the system is actually working as intended, especially when automation is involved.

A Resident A installed a private electric unit for better thermal comfort. This of course, uses more energy. Interestingly, this commercial radiator warns not to block its vents, though no such labelling is found in the heating systems installed with the house and skid.

Resident A experienced an issue in the past where the hard water running through the radiator had caused scales. This was difficult and time consuming to diagnose. Both residents had experienced signal issues from the interface to the main unit in the shielded skid, which also took time to resolve.

Resident B experienced that their cooling system was broken in the middle of a heatwave. Automated systems have difficulty maintaining appropriate temperature during spring and autumn. Since cooling is required for a relatively short period of time, it is also difficult to know if the systems are working correctly before the time when it is required.

The skids have a functionality to generate excess hot water, beyond the normal capacity of the boilers and the buffer tank. This requires accessing the skid to actuate a tiny button within it. Interviewed residents did not know of this feature.

Within the context of social housing, it is plausible to have large families living in a small space. Such residents may need to use the function regularly, which is inconvenient to access. The mechanism of the system is unknown, though typically such systems work by diverting power from room heating to heat the additional water. Not knowing the how the system functions may lead to suboptimal use from the residents.

Fig. 36: Private electric heating unit installed in living room

Fig. 37: Radiator

Fig. 38: Temp control interface

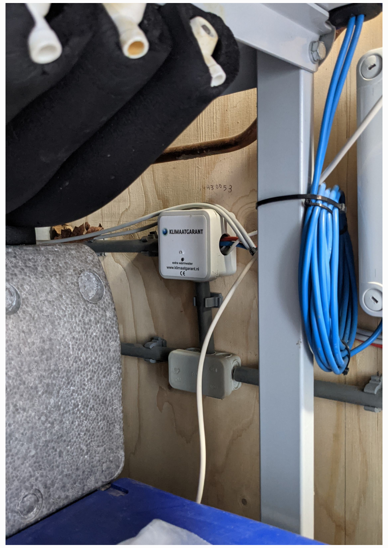


Fig. 39: Hot water button

3.2.3 Skid and Maintenance

The external skid is perceived more like a toolshed or a meter box, instead of a proper part of the house. However, it is still seen as part of the property, if not necessarily the residence (Boess, personal communication, May 2024).

The components within the skid are confusing and intimidating. For residents, it is not apparent which systems can be interacted with, and which ones should be left alone. To unplug the ventilation system, I had to first identify the ventilation unit, locate the power cable, and trace it all the way back to the socket. I had trouble distinguishing the similar looking wires from wach other.

The envelop of the skid was observed to be notably larger than the components inside. This is because more space to work with makes it easier to find a suitable packing orientation for the components within. There can be even more available space in a particular apartment's skid if skid components are shared across units. This can be seen in Vlaardingen, where the top floor only has the heater and MVHR unit.

Residents have been known to use the available space in the skid as a storage cabinet, sometimes damaging the components within, and making maintenance difficult. Having more available space within the skids makes it more likely for residents to store less-frequently used items inside.

Fig. 40: Skid internals

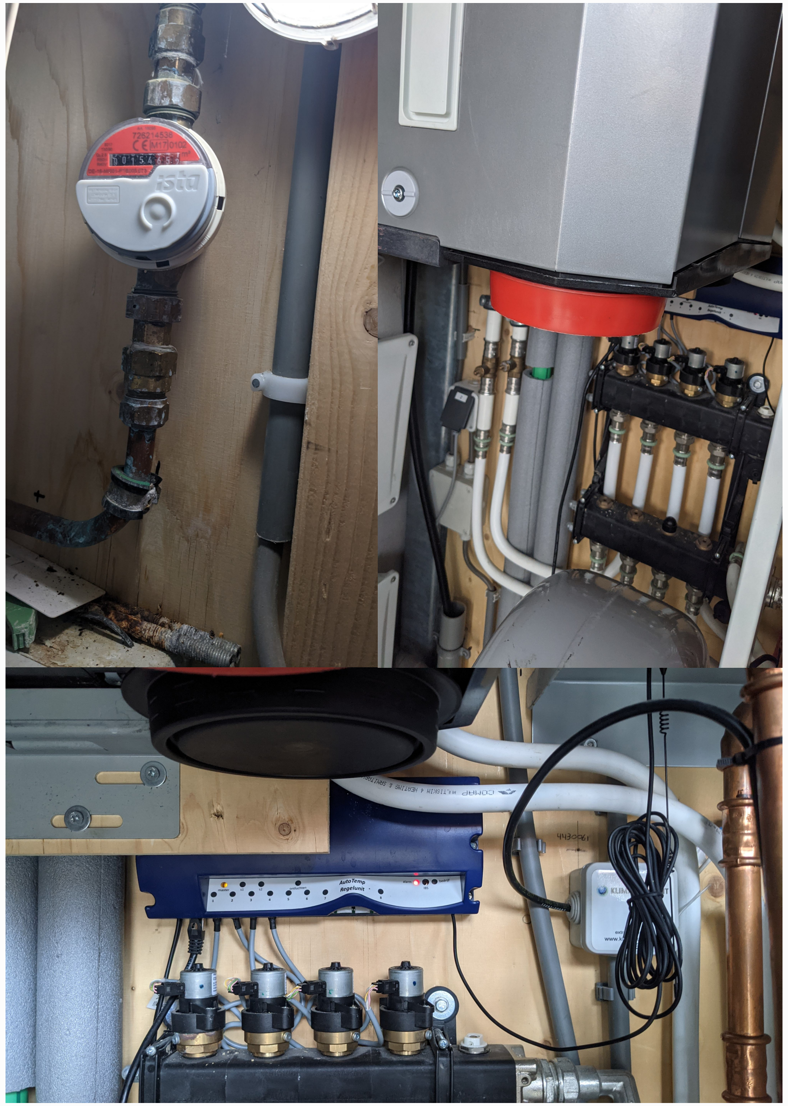


Fig. 41: Skid internals

Changing the ventilation filters is the only interaction that an average resident of social housing would likely have with their skid, if at all. In rare cases, residents may need to access the additional hot water. Some residents with the inclination and knowledge may carry out other minor tasks, or assist with diagnosis to expedite the maintenance process.

Problems with these kinds of HVAC systems are often only discovered when catastrophic failure occurs. The third-party maintenance crews don't always have a complete understanding skid systems. Resident A had an issue that a maintenance crew attempted to fix multiple times over the span of months. This required access to the skid through the resident's property every time. It was eventually escalated to the OEM, that resolved the issue in a single visit. I believe this scenario to be a common for social housing.

Proper installation of the skid and its components is important for the sustained functioning of the system. However, there is no way for residents to verify installation errors. Installers may make errors, employ quickfixes, skip out on organisation such as cable management. The impact of these decisions are only felt in the long term.

The layout of the skid itself may make maintenance difficult. For instance, in the Vlaardinen skids, the door of the skid opens past the first filter of the MVHR unit, which makes access difficult. The grills on the floors have large gaps through with tools or belongings can fall, damaging equipment on lower floors and causing inconvenience.

Fig 43: Resident storing equipment in skid

Fig 44: Damaged ventilation unit

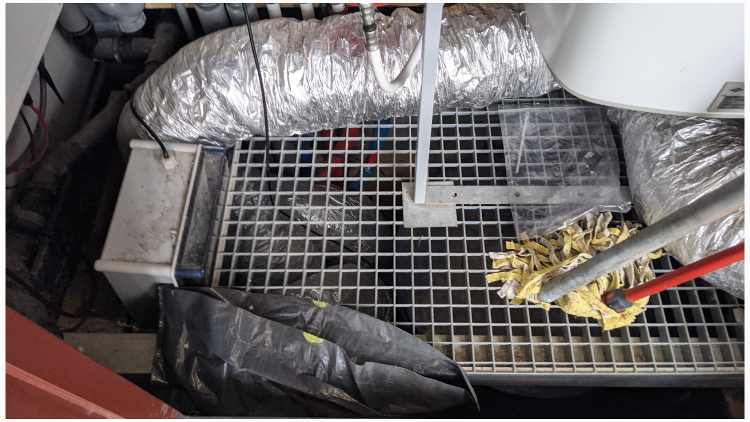


Fig 42: Grill on skid floor

Key Takeaways

- The ventilation system is complex and unintuitive.
- Minor non-designed interactions such as pulling the power cord cause great physical strain
- The MVHR system gets harder to interact with when it is within the skid.

Chapter 3: Conclusion

This section has presented observations & insights about how residents interact with the system & how the system functions. The next step is to conduct a stakeholder analysis specifically for social housing.

4. Stakeholder analysis

This chapter combines insights from various stakeholders, along with those gathered from user interviews in the previous chapter, to form a stakeholder analysis. This analysis is critical to address the project's complexities effectively.

4.1 | Stakeholder Mapping

In social housing projects, understanding stakeholder wants and needs is essential due to the complex decision-making process that excludes the direct involvement of residents.

Unlike a typical business-to-customer model, numerous parties contribute to the decisions regarding which systems to implement. Therefore, it becomes crucial to understand the perspectives of these other stakeholders.

Instead of the common interest vs. influence mapping, this analysis uses an incentive vs. influence approach. "Incentive" offers a rough estimate of the potential benefits each stakeholder could derive from the proposed solutions, providing insights into their willingness to invest time and resources into implementing changes. This differs from "interest," which merely indicates a stakeholder's motivation for change. For example, residents, although having low interest, possess high incentive since they would benefit most from improvements to the systems in their homes.

The terminology used to describe the stakeholders is shown in the figure. This terminology will be used in later chapters as well.

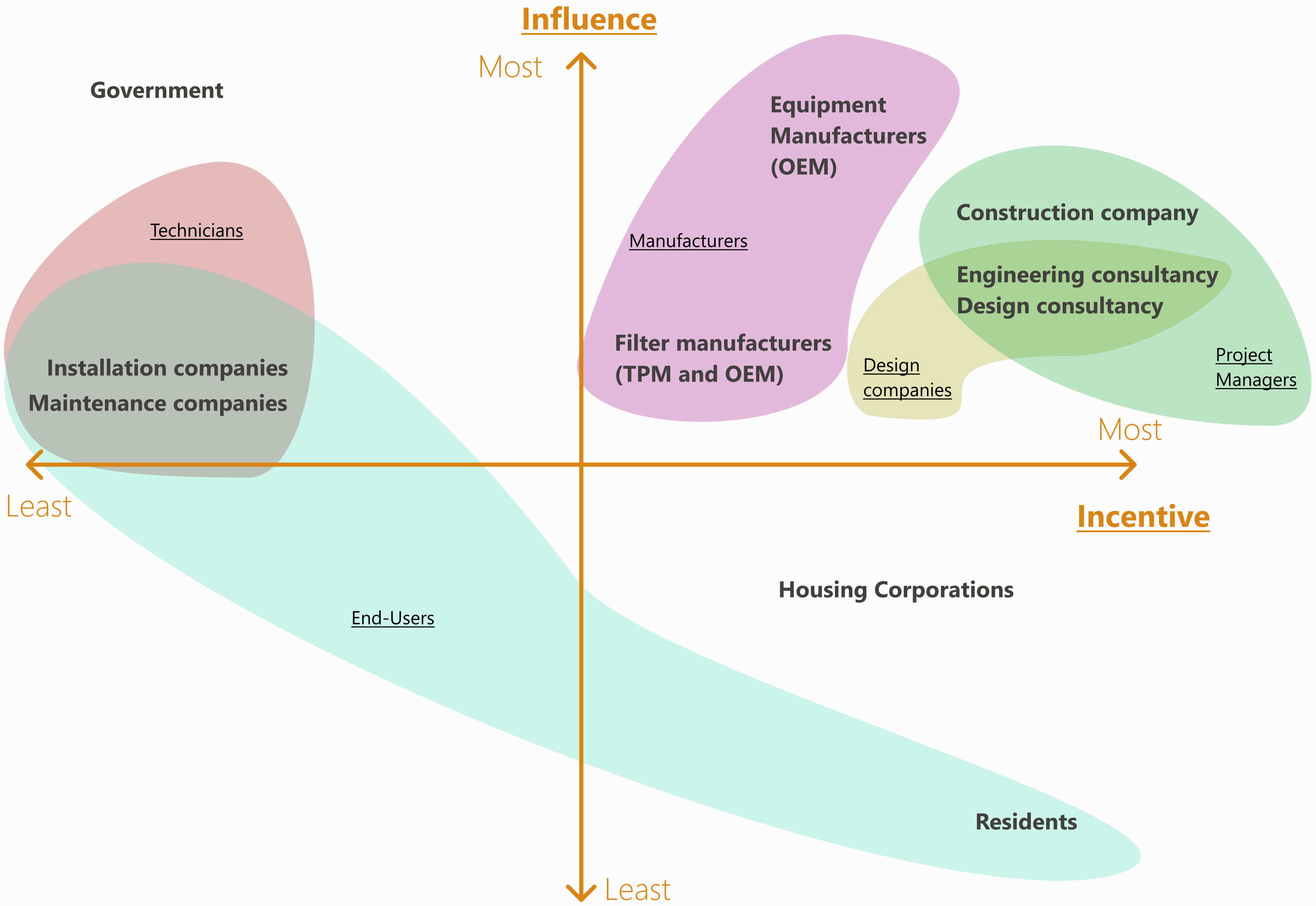


Fig. 45: Stakeholder mapping.

Housing Corporations

Housing corporations, as the stakeholders funding the project, hold the final decision-making authority. Their primary concern is finding cost-effective solutions that deliver good value while keeping expenses manageable. They generally prefer that residents do not engage in maintenance tasks; however, they recognize that residence managers may request residents to perform minor tasks if they possess technical skills. These corporations emphasize strict adherence to procedures and prefer to follow established protocols meticulously. Additionally, decisions are typically made collaboratively as part of a consortium.

Project managers (Construction company, engineering consultancy, design company)

All three stakeholders help execute construction of the project, and can have varying roles. The construction company takes the lead, consulting with design companies to ensure the technical details and implementation aspects are addressed effectively.

Their focus is on technical precision, implementation strategies, and cost management. They are responsible for selecting the best implementation approach within the constraints of available resources. In the context of skid systems, this involves planning the components, configuration, and manufacturing or installation processes. When multiple parties are involved, responsibilities are often more specialized and divided among the collaborators.

Government

The government creates laws to ensure the well-being of citizens. Given its broad scope, it is too vast of an entity to approach at this stage of the project. Nonetheless, every stakeholder must adhere to these laws, which guide the overall framework within which projects are developed and implemented.

Original Equipment Manufacturers (OEMs)

OEMs are responsible for creating the machines and designing systems primarily from an engineering perspective. Their designs are not specifically optimized for skid-based systems. Manuals provided by manufacturers are often not well-updated, with the assumption that users, as well as maintenance and installation personnel, will adapt as needed. Manufacturers typically advocate for the use of original filters and tend to offer overly cautious advice, likely driven by liability concerns.

Filter manufacturers (TPM and OEM)

Original Equipment Manufacturers (OEMs) typically outsource the manufacturing of filters, while third-party filter companies (TPMs), such as Econox, focus on compatibility and cost reduction. Third-party manufacturers may not offer extensive quality assurance beyond ensuring core functionality.

Their advice on filter change frequency may be overly cautious, potentially pushing for filter obsolescence. Although they must adhere to ISO standards, their explanations of these standards can be unclear. Additionally, the information provided to retailers by filter manufacturers may lack accuracy and thorough fact-checking.

Installation companies
Installation companies are responsible for fitting components into skids and connecting them to residential systems. These companies are often third parties with varying skill levels and attention to detail. Unskilled workers can make installation errors that may not be immediately apparent but can lead to compounding issues later on. The incentive for high-quality work can be low, as the focus is often on completing tasks quickly and cost-effectively.

Maintenance crews
Maintenance crews serve as the first point of contact for servicing and upkeep. Typically third-party contractors, they may not always be familiar with specific machines and exhibit varying skill levels and attention to detail. OEMs often limit their involvement in maintenance to particular scenarios, leaving these crews as the primary option for ongoing issues. This can be problematic, especially in social housing, where unresolved problems might require multiple visits. Additionally, maintenance crews generally have low incentives for high-quality work, further compounding the challenge.

Users
Users are the most directly affected stakeholder group in terms of health, quality of life, cost of living, etc. but hold the least influence and interest in the system. They often prefer the path of least resistance and but could to be convinced to change their behavior with time. Effective solutions must therefore account for their tendency to seek simplicity and ease of use.

Key Takeaways

- Social housing in the Netherlands is a complicated process with many stakeholders.
- Designs must be made for all end-users, i.e. residents, maintenance and installation personnel.
- For designs to be implemented, they must target stakeholders with influence and incentive.

Chapter 4: Conclusion

This chapter has presented a stakeholder analysis and defined certain terminology. With this knowledge, the process of ideation can begin.

5. Design Direction

This chapter outlines the process of selecting a design direction. It begins with generating various disjointed ideas, which are then organized into five distinct solution spaces. These spaces are evaluated using a novel method, leading to the selection of a final design direction.

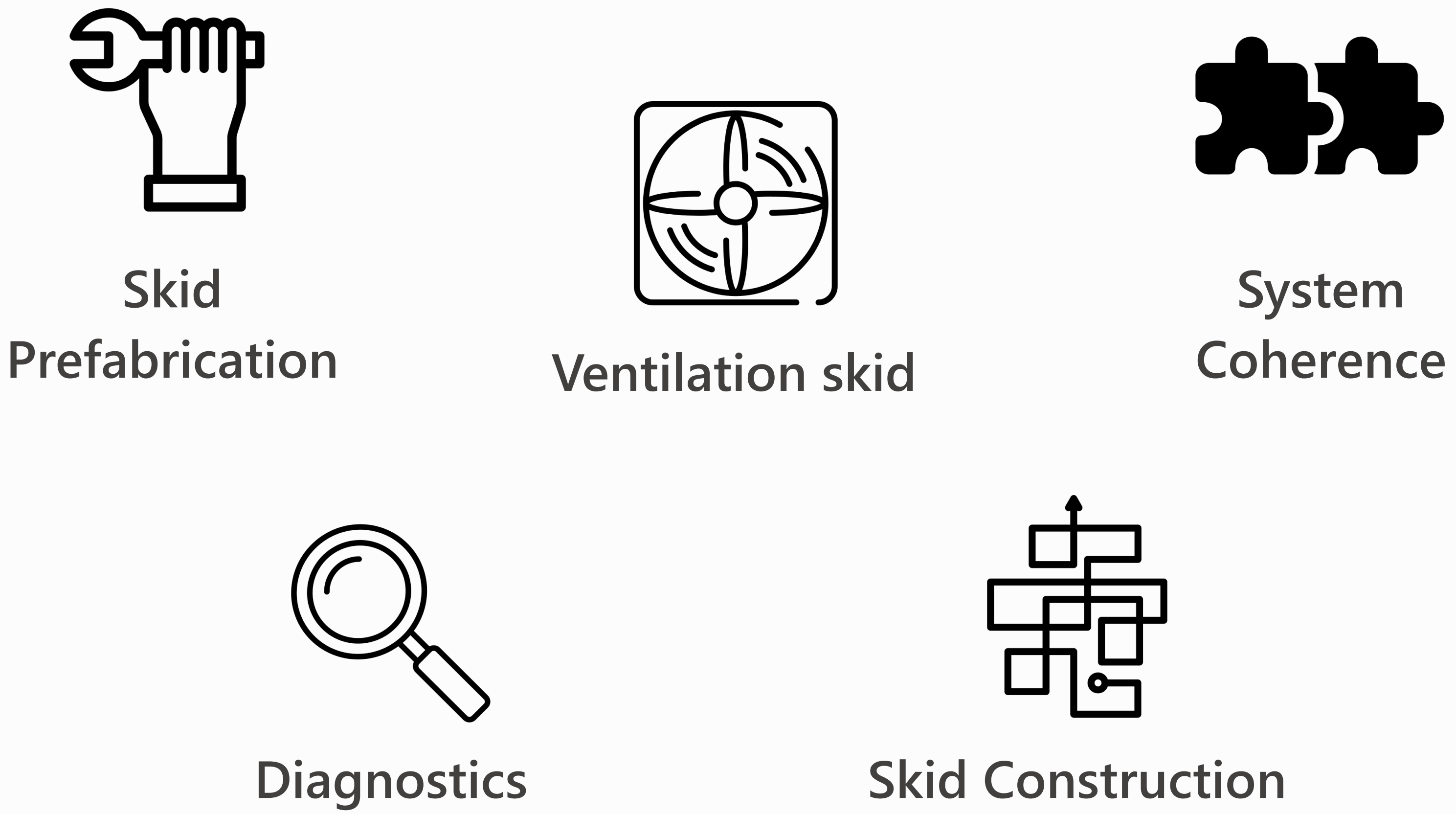
5.1 | Solution Spaces

With an understanding of the system and its context, ideas for potential solutions were mapped out. Several key factors were taken into consideration.

In social housing, residents are often less involved in the maintenance process, and Housing Corporations typically prefer that residents do not handle maintenance tasks themselves. As a result, Maintenance Companies are likely to become the primary end-users for redesigned interactions. Similarly, Construction Companies might delegate the setup of these systems to specialized Installation Companies. Government regulations also play a critical role, influencing all stakeholders, while Original Equipment Manufacturers (OEMs) operate on their own timelines.

Given these complexities, both complete system redesigns and retrofits to accommodate existing systems were considered, as it may not always be practical or possible to develop a completely new system.

The ideas generated were then organized into five main solution spaces: Skid Prefabrication, Diagnostics, Skid Ventilation, Skid Construction, and Miscellaneous Improvements. These solution spaces will be detailed in the following subsections.



5.1.1 Skid Prefabrication

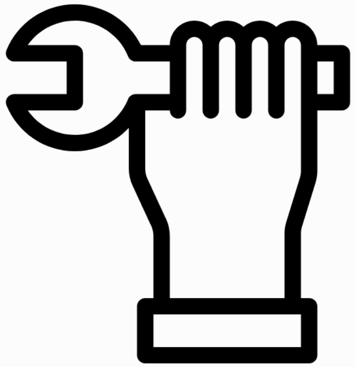
Installation of skids requires skilled labour, which the market is currently facing shortages for. If the prefabrication process of skids were improved, it would lower this skill requirement, and also reduce the number of installation errors.

Prefabrication also creates standardisation, which reduces potential points of failure, making maintenance of systems easier down the line.

Considerations

The typical pre-installation process is not known. Exploring this area would require contacts of installation crews, which would need to be interviewed. I would also require to gain a strong understanding of the installation errors, of which there are many. This would require deep technical research alongwith the interviews, as installation crews may be biased when revealing information about errors.

Prefabrication has limitations and cannot work for every project. For instance, the units in Nijmegen from Bosch Nefit are fully self contained. They were lowered into the apartments via a crane, and a roof was built over them. The skids in Vlaardingen are not homogenous. Skids on each floor have different components and configurations. This means that a different approach would be needed to prefabricate these skids, if it were possible at all.



Skid Prefabrication

Fewer installation errors and quickfixes

5.1.2 Diagnostics

Measurement devices are used by professionals to verify if systems are working as intended and to diagnose problems. For instance, an anemometer is often used to measure flow rate for inlet and exhaust vents.[Fig 1 and 2]

However, residents do not usually have access to these expensive technology. An easy to use diagnostic tool for residents could help them verify installation errors, and engage in regular checks, identifying issues before they snowball into more severe problems.

Certain classes of errors could be designated for equipment manufacturers directly, bypassing service techs and saving time and money. Lastly, the tools themselves could be redesigned to make problem diagnosis easier for service techs.

An improved pre-installation analysis would reduce the number of unexpected events, and lead to fewer workarounds implemented.

<u>Considerations</u>

This solution space requires an understanding of all possible errors related to the installation and maintenance of the skid and associated HVAC systems. Additionally, the process of diagnosing errors and the equipment used needs to be extensively researched.

The process and equipment used would not only change between different skid setups, but also installation and service companies. There is also a limitation of the kind of diagnostics a consumer might be able to do for safety reasons.

Fig. 46: Anemometer

Fig. 47: Device for accurate measurement of exhaust flow rate

Diagnostics

Problem discovery and diagnostics

5.1.3 Skid Ventilation

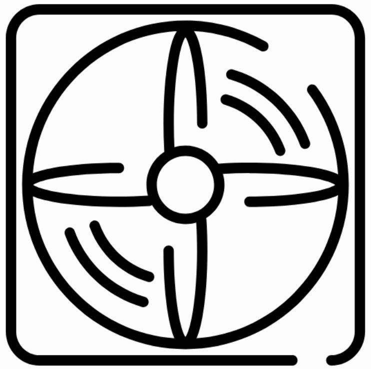
Since changing filters is the most common and important task for consumers, the physical and cognitive strain of the task must be lowered. The primary goal is to ensure the ventilation filters are regularly cleaned.

This could be achieved by making the filters easier to access, hold, and manipulate. Access to cleaning equipment could be improved. The filters be modified to last longer. The filter change system itself could be modified to improve the interaction, and a more convenient method to cut the power to the unit could be implemented.

Considerations

Changing ventilation filters is an important task that residents can easily carry out. Out of all the components of the entire HVAC system of the house, this the easiest task with a near non-existent chance of injury. Maintenance or Installation companies, which have the knowledge but may not have the incentive, may also carry out this task. Therefore, redesigns in this solution space cannot rely on the ability or willingness of the end-user to follow proper procedure.

This solution space requires an understanding of underlying causes of physical and cognitive strain for maintenance interactions with the ventilation system. Function of the MVHR unit, and the constraints within which it functions, including those imposed by the skid must be known to propose system modifications. These factors can be independently researched without need of much external reliance.



Ventilation skid

Improve interactions with system

5.1.4 Skid Construction

The manner in which skids are constructed affects how end-users interact with the system.

Components within the skids could clear designations to have components relevant to the residents stand out. For instance, since residents have to pull the plug for ventilation systems, the cord and plug could be of a different colour.

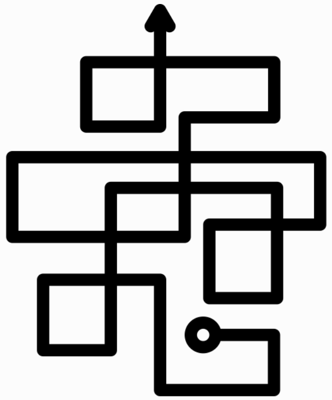
Changing how the components are positioned could make systems easier to maintain by all end-users. Residents could have a limited access point, allowing interactions with only the systems relevant to them, such as the MVHR unit. This restricted access would reduce unnecessary resident-skid interaction, preventing the skid from being used as a storage unit, causing potential damage to the components.

Alternatively, since residents consider the skid to be part of their property, they might want access to it. The skid construction could be modified to allow for safe storage of items by isolating empty sections from the HVAC components. This could be further modified to encourage storage of specific components such as a vacuum cleaner, with a convenient socket nearby for filter cleaning.

Considerations

Exploring skid construction requires an understanding of the guidelines and technical constraints for designing skids. It could be possible to find this information through research and the assistance of the stakeholders previously interviewed.

Once the constraints are determined, optimal component position and means of access could be explored through prototyping or modelling. The solutions would primarily focus on the residents' perspective, which would require a more thorough understanding of psychology and behaviour. It would be challenging to secure interviews with technicians to validate assumptions and make improvements from their perspective.



Skid Construction

Reduce physical and cognitive strain

5.1.5 System Coherence

The HVAC components that are present outside of the skid may have been neglected as well.

Actuation of buttons or screens for ventilation and heating system could be made less physically strenuous. The interface could be made more clear and understandable. Alternative means of feedback for the heating and ventilation systems aside from the change in heat or noise could be devised. This would help residents understand how the system reacts to their inputs.

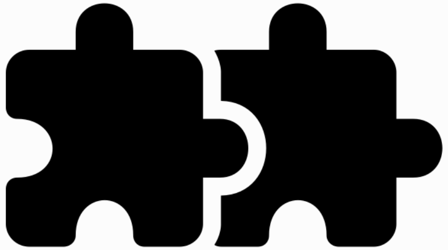
I notice that inlet and exhaust valves are often dirty in most homes, not just the ones I visited. They can also be obstructed. Changing the location of the vents to be more in-line with resident behaviour could address this issue. The designs could be modified to facilitate cleaning and prevent the airflow rates from accidentally being changed.

Considerations

This solution space explores problems with HVAC components that residents interact with in general, not restricted to skids.

However, removing the context of skids would again increase the scope of the project. It would require and exploration of a number of existing systems to find how different OEMs tackle user experience for their products, and to find other problems to tackle.

For the problems that have already been found, research into technical limitations would have to be conducted. It is likely that this solution space would be selected in combination with another, if the specific redesigns are found to be easy to implement.



System Coherence

Redesigns for components outside the skid

5.2 | Chosen design direction

Choosing a direction from the clusters of ideas is a complex task due to the varying quality and potential of the individual concepts within them. Existing evaluation systems are often better suited for fully developed concepts, and these ideas are still in their early stages.

Moreover, while the focus is on the Vlaardingen skid, I cannot assume it to be representative of all skids. Some issues may be unique to this specific case, so the research must also address problems inherent to HVAC systems as a whole.

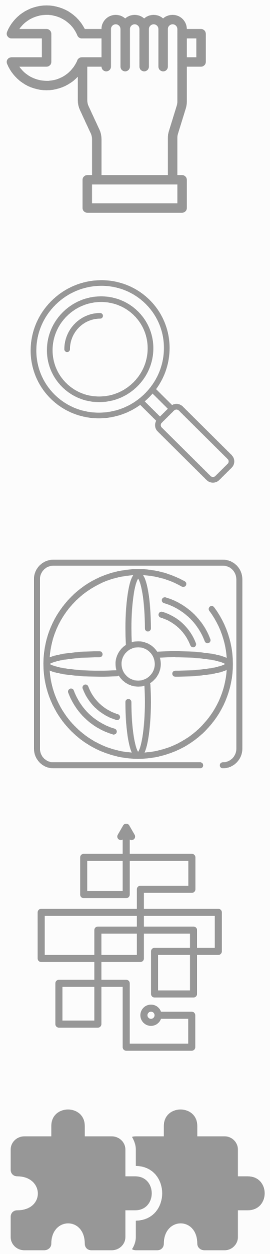
The evaluation process must balance the potential benefits to residents with the likelihood of implementation by stakeholders. Additionally, the selection criteria must account for my personal skills, resources, and limitations to ensure the project's feasibility.

To navigate these challenges, I devised my own decision matrix. The selection criteria are explained in the following section.

5.2.1 X-Axis: Alignment Quality

In the x-axis, I use a metric called "alignment criteria." This metric primarily addresses the feasibility and viability of the solution spaces. Essentially, it measures how realistic it is to pursue a particular design direction given the available timeframe for the thesis and my personal skills. It also takes into account whether redesigns in this space are likely to be adopted in the market, based on the stakeholder analysis.

To evaluate the solution spaces, I apply a weighted criteria method, where individual parameters are assessed to determine how well they align with my requirements. The parameters and the rationale behind their assigned weights are explained in the next section.



Unknown factors ↓↓

Working with incomplete information is an intrinsic aspect of this project. However, at this stage is vital to choose a solution space that has as few starting assumptions as possible, and the assumptions that remain should be possible to independently validate. Spaces that have critical unknowns that need expert consultation to proceed will be extremely difficult to proceed with. Thus, this parameter is given the greatest weight.

Ease of prototype and testing ↑↑

User testing and prototyping is an important part of the thesis, especially due to the focus on feasibility. Solution spaces for which I can picture a general idea of how I might prototype and test individual concepts are strongly preferred, especially due to the time constraints.

Stakeholder Focus ↑↓

The possibility of the solution being implemented and effectively used depends on the stakeholder that is targeted. If the solution requires cooperation from the intermediaries such as Installation Companies and Maintenance Companies, it is unlikely to be used, as they have little incentive. Solutions that target Manufacturers or Residents are much more likely to work.

Innovativeness ↑

Novel ideas are given preference, since the goal of the project is to come up with principled solutions.

Ease of implementation ↑

Solutions that are feasible and viable to implement by stakeholders with influence

Solution Space Synergy ↑

This parameter is a bit of a bonus. Certain solution spaces can synergise with each other and help tackle problems from different perspective. While I don't have time to fully explore these, they may still be a useful consideration.

Unknown factors	30
Ease of prototyping & testing	25
Stakeholder focus	15
Innovativeness	15
Ease of implementation	10
Solution space synergy	5
TOTAL	100

Fig. 48: Criteria and their weights

Weighted Criteria

		Skid Prefabrication		Diagnostics		Skid Ventilation		Skid Construction		System Coherence	
Unknown factors	30	3	90	2	60	8	240	7	210	5	150
Ease of prototyping & testing	25	2	50	1	25	7	175	7	175	6	150
Stakeholder focus	15	5	75	3	45	9	135	10	150	10	150
Innovativeness	15	7	105	8	120	10	150	7	105	2	30
Ease of implementation	10	3	30	4	40	6	60	6	60	9	90
Solution space synergy	5	5	25	5	25	7	35	10	50	4	20
TOTAL	100	375		315		795		750		590	

Fig. 49: Weighted criteria method to check alignment quality

From the weighted criteria, I found skid ventilation and aligned to the requirements best, followed closely by skid construction.

5.2.2 Y-axis: Impact Potential

Impact potential is the metric on the other axis. It aims to encompass the potential impact improvements within a solution space can have.

With this metric, I measured impact for all stakeholders. Priority is given to a design direction that can improve the quality of life of residents. I considered the potential impact of solving both ubiquitous and niche issues.

Since residents are historically neglected when designing systems, it seemed appropriate to prioritise their benefit while choosing a solution space.

It is difficult to assign a meaningful numerical value to this metric. I assigned relative positions for the impact potential of each solution space instinctively.

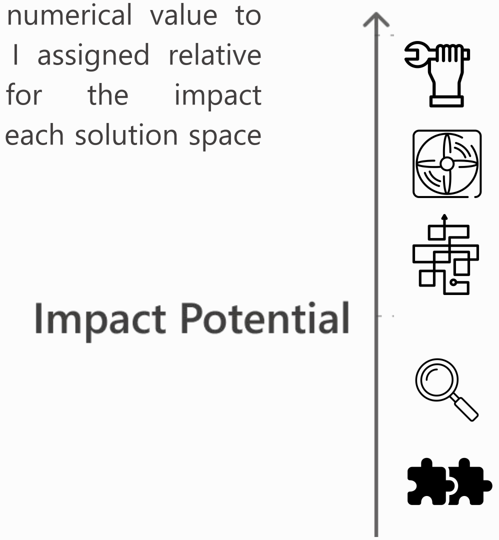


Fig. 50: Ranking of impact potential

5.2.3 Decision Matrix

I inputted these values into the matrix. Skid ventilation wins out as the solution space in the top right of the quadrant. Choosing this direction would give greatest value for the effort spent.

Ventilation scores high in impact potential due to its ubiquitous nature. The solutions could be implemented even outside of the context of a skid. Additionally, I could envision how to prototype the concepts, and assumptions could be validated without external help.

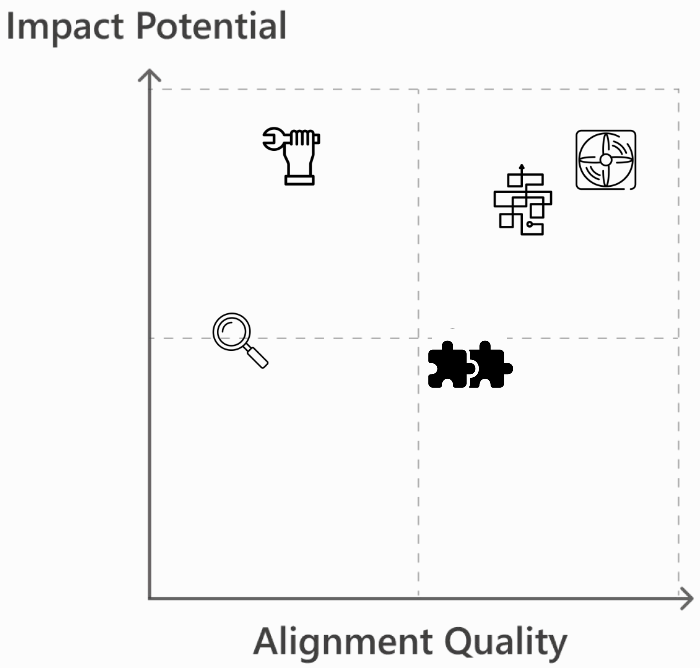


Fig. 51: Decision Matrix

Skid construction trailed closely behind. I decided to also explore this direction, a little, in case it was possible to generate interesting insights. However, the priority was still skid ventilation. There could also be possible synergy between these two solution spaces.

Through research, I learned that skid prefabrication would have the greatest impact. It would address the shortage of skilled labour, reduce installation errors, and save costs. Unfortunately, this solution space has too many unknowns that are critical to proceed, and is thus eliminated. Diagnostics and miscellaneous fixes do not give enough value for the difficulty of execution, and are also eliminated.

Key Takeaways

- Skid ventilation is the chosen solution space to move forward with.
- This was chosen by an evaluation matrix I devised to give equal importance to the executability of the project and the needs of the users.

Chapter 5: Conclusion

Amongst the various solution spaces, ventilation systems has emerged as the most suitable area. Choosing this space gives clear and concrete direction for further development.

Concept Development

6. Ideation and prototyping

This chapter outlines the design approach taken, where prototyping was initiated early to gain a detailed understanding of the system. By simultaneously developing and refining multiple concepts, deeper insights were achieved, leading to a continuous feedback loop of ideation, research, and prototyping. The focus was primarily on maintaining the MVHR system, with an emphasis on retrofitting solutions.

6.1 | Prototyping Framework

Since there are many manufacturers of filters and ventilation systems, each with their own constraints and expertise, I chose to prototype to find principle solutions rather than an exact design.

This means that the focus was not on ensuring perfect compatibility with a particular system, rather determining the principles by which neglected areas could potentially be addressed.

I compare two MVHR systems, the ITHO HRU 300, and Zehnder Comfoair Q350/450/600. Both these units have different filter change mechanisms, and together they cover how most systems in the market operate. The former is the unit found in the Vlaardingen apartment skids, and the latter is a popular option when it comes to MVHR Units.

The ITHO unit is chosen as the template for prototyping. The prototype consists of two lasercut "cassettes" that are slotted into a foam core. The slot of the actual unit is curved, but for simplicity, the cassette prototypes are straight.

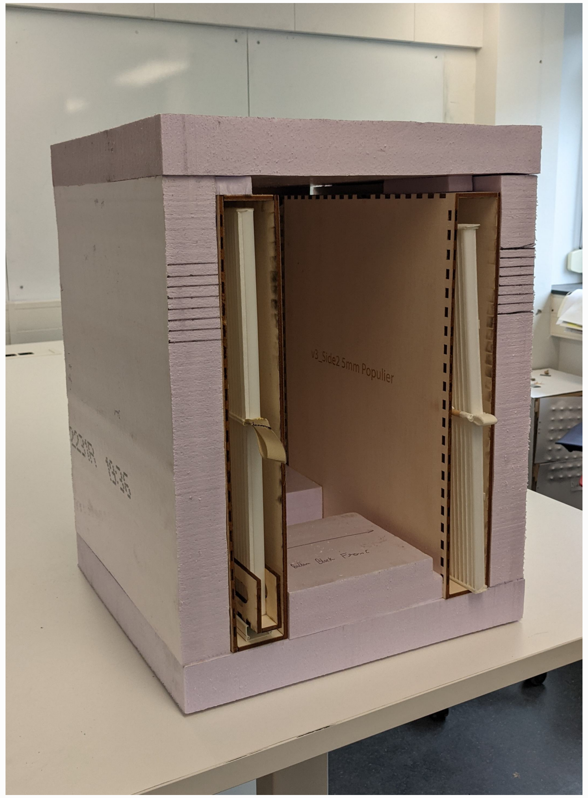


Fig 52: Ventilation unit prototype

Fig 53: ITHO HRU 300

Fig 54: Zehnder Comfoair Q450

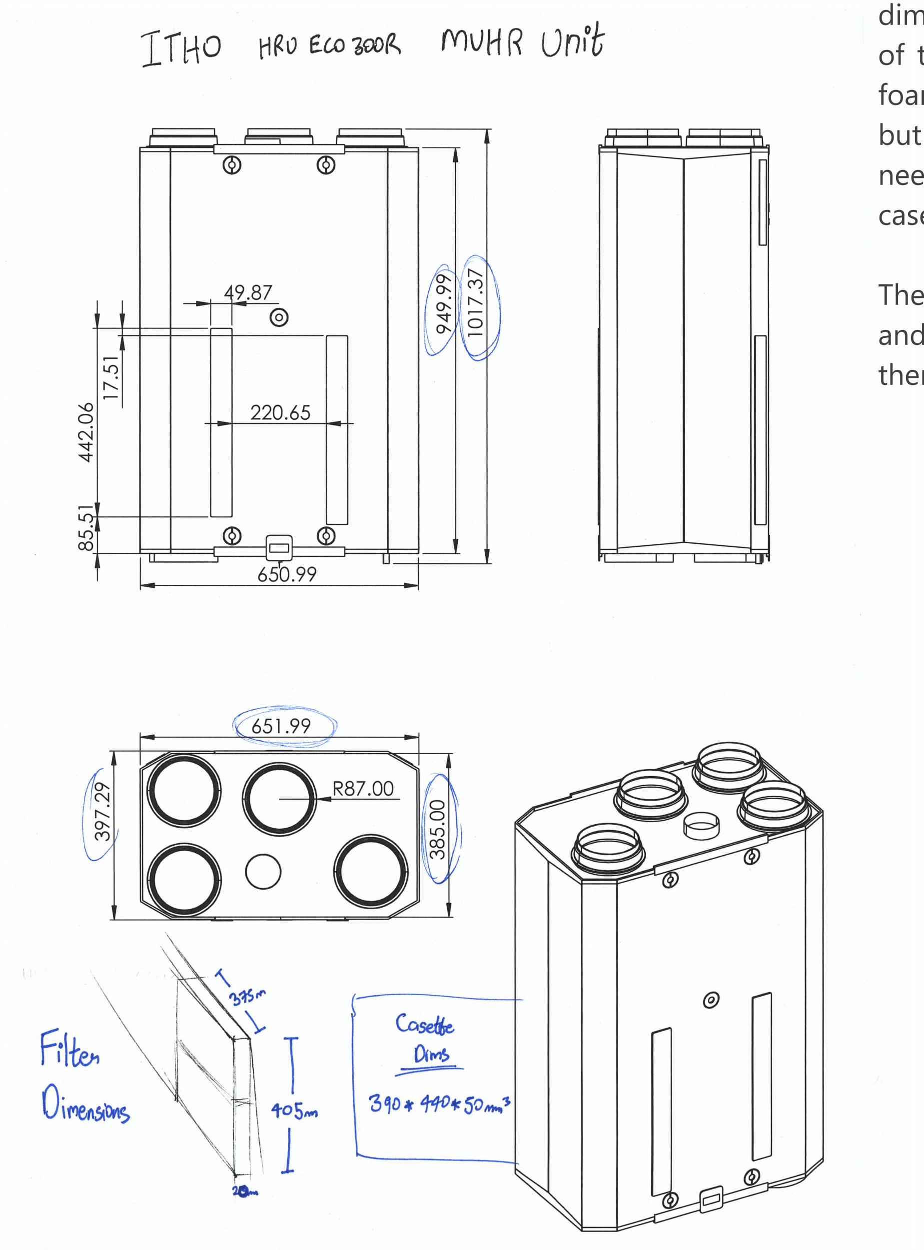


Fig 55: Drawing file ITHO HRU 300

The foam box is made referencing dimensions from an official drawing file of the ITHO unit [1]. Initially, making a foam box to a 1:1 scale was considered, but was found unnecessary, as it only needed to comfortably house the casettes.

The final version was built to be sturdy and lightweight, using the cassettes themselves as bracing.

Fig 56: Box constructed with XPS foam and wood glue

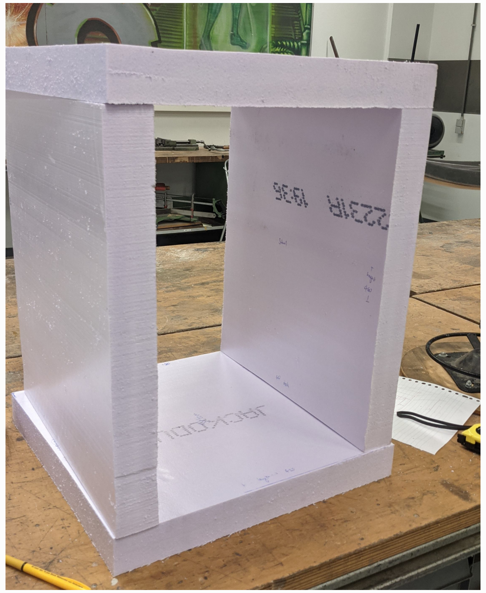


Fig 57: Basic frame of ventilation box

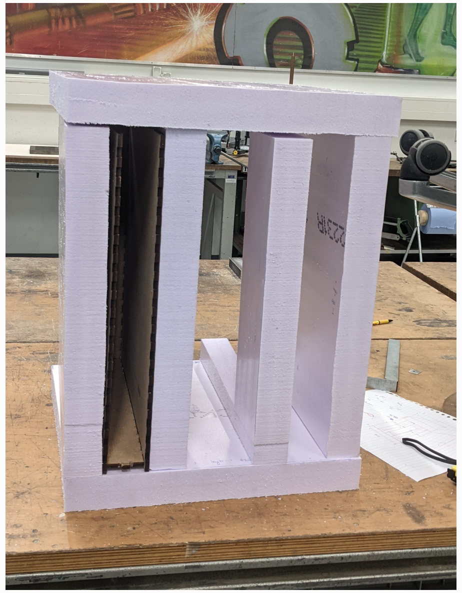


Fig 58: Initial design of ventlation box

The cassette was initially cut out of 6mm MDF wood, and press fit together. The first prototype was heavy, and I had to saw off some teeth to make the fit easier. [Fig 1] The second version improved on the design of the joints, and was cut out of 5mm populier, which is lighter and warps less. I added a slit to the back end of one of the sides to make it easier to disassemble the side if needed, and create a small access point.

Fig X: Lasercut box v1 parts

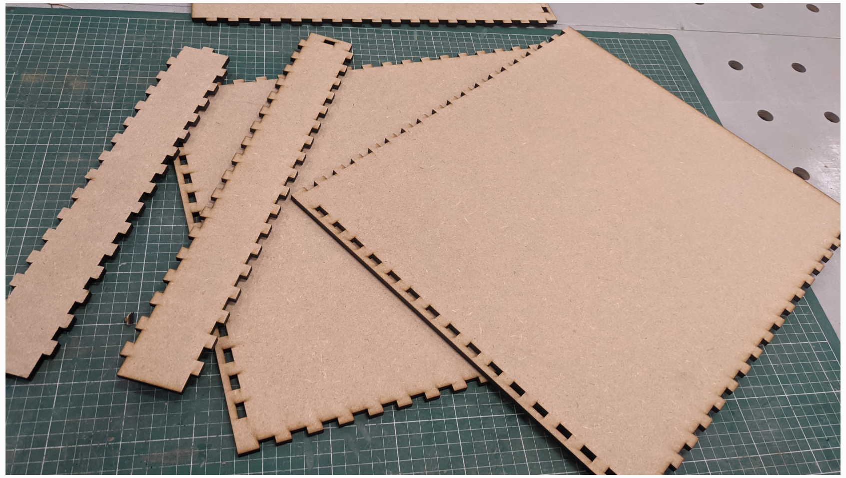


Fig 59: Cassette v1 lasercut components

Fig 60: Cassette v1 and v4

Fig 61: Cassette internals with access slit

Key Takeaways

- Early prototyping revealed details that ideation alone couldn't uncover.
- The design process focused on rapid iteration and refinement.
- The focus was primarily on MVHR system maintenance, with an emphasis on retrofitting.

Chapter 6: Conclusions

Rapid prototyping raised many research questions and gave many ideas for concepts. This research is explained in the following chapter.

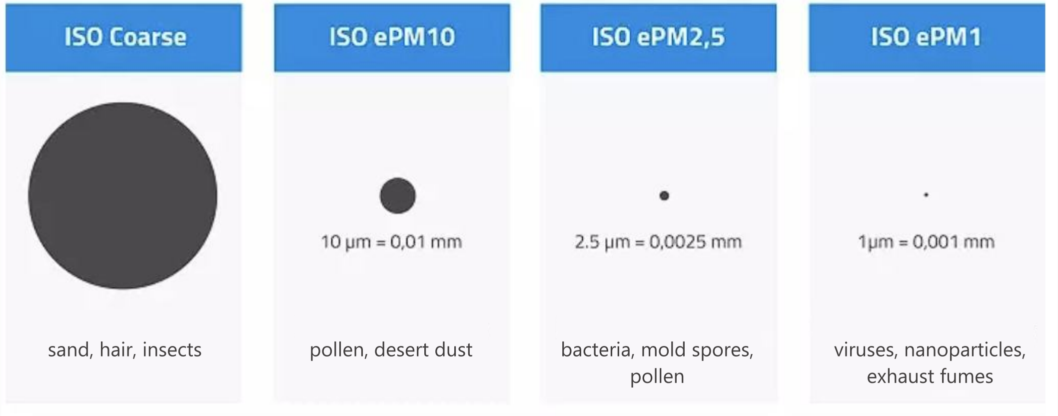
7. Research and Analysis

This chapter delves into the questions that emerged during the prototyping phase. It provides a detailed analysis of filters and MVHR systems, examining the root causes behind user pain points and exploring potential solutions to address them.

7.1 | MVHR Filters

7.1.1 Filter grades

The most commonly used filters in ventilation systems are G3, G4, M5, M6, F7. This is labelled according to the EN779 class, which has been succeeded by ISO 16890 (ISO 16890 | WTW Filter Store, z.d.). However, these older classes are still colloquially used.



- **ISO COARSE:** This is the coarse dust (sand, hair, insects, etc.). This coarse dust is harmful to your WTW installation.
- **ePM10:** These "coarse" particles originate from traffic and industry. These particles can remain in the lungs.
- **ePM2.5:** These fine particles can reach the alveoli.
- **ePM1:** These ultrafine particles are the most harmful variant of particulate matter, because these particles enter the bloodstream directly via the lungs and are thus spread to the organs.

Fig. 62: Filter grades vs efficiency (ISO 16890 | WTW Filter Store, z.d.)

The figure above shows the relation between ISO 16890 classification and the EN 779 filter classes. Particulate matter is classified by size, and the table shows the extent to which filters of a particular class protect against different sizes of dust particles.

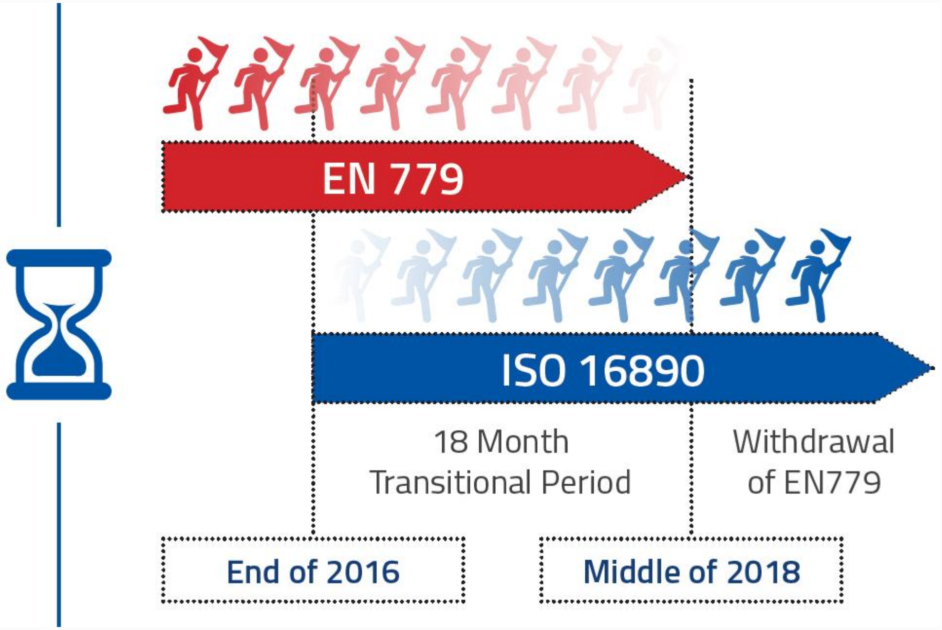


Fig. 63: (ISO 16890 | New Standard For Air Filters – Ulpatek, z.d.)

Fig. 64: Filter comparisons (Itho Daalderop, 2020)

The table shows the relation between ISO 16890 classification and the EN 779 filter classes. Particulate matter is classified by size, and the table shows the extent to which filters of a particular class protect against different sizes of dust particles. This table is an approximation since the testing and evaluation of procedures of ISO 16890 and EN 779 differ greatly.

The G series of filters is considered a coarse filter. G3 filters, which are typically fiberglass (Filters, z.d.) are usually used when the unit is installed. Switching to pleated filters such as G4 grade or higher is recommended once the residence is occupied (Itho Daalderop, 2020b).

G class filters can capture contaminants from 3.0-10.0μm, such as mold spores or cement dust. However, as seen from the chart G3 filters only capture 45% of coarse particulate matter, while G4 filters retain 90%. G3 filters are thus insufficient for regular use, and may still cause respiratory problems (Filters, z.d.).

F7 filters, also called hygiene filters, capture contaminants from 0.3-1.0μm such as bacteria, and smoke. The F7 filter is finer than the G4 filter and therefore provides more thorough air filtration. F7 filters can be useful for residents with allergies, and can also filter out certain bacteria and fungi (F7 And G4 Filters: What Are The Differences?, 2024).

A filterset for regular use typically contains a G4 filter for air leaving the house (return filter), and a G4 or F7 filter for air coming into the house (supply filter). Thus, these are the only filter grades that I consider for my design.

Filter class	ISO coarse	ISO ePM10	ISO ePM2,5	ISO ePM1
G3	> 45 %	-	-	-
G4	> 90 %	-	-	-
M5	> 95 %	> 50 %	-	-
M6	> 95 %	> 60 %	50 - 60 %	-
F7	> 95 %	> 85 %	65 - 80 %	50 - 65 %
F8	> 95 %	> 90 %	> 80 %	65 - 80 %
F9	> 95 %	> 95 %	> 95 %	> 80 %

Fig 65: Old filter classes vs ISO comparison (Dijkmeijer, z.d.)

Fig 66: G4 and F7 filters


Fig 67: G3 filters

7.1.2 Filter orientation

Filter orientation is important. If filters are put in the wrong orientation after cleaning, that could cause the residual dust to be sucked into the machine, damaging the components.

This information is difficult to find in the manuals or the official websites. There is a lot of conflicting information online due to the different types of filters and grades which makes it difficult to ascertain the facts.

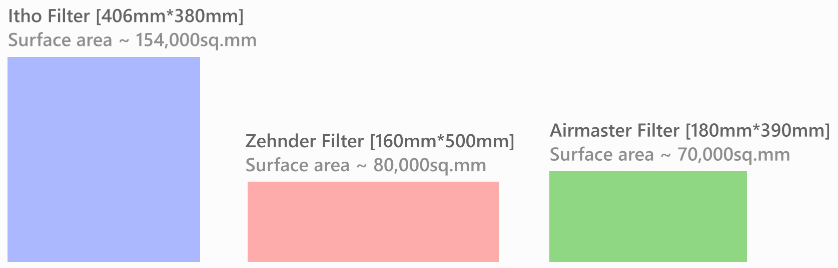


Fig 68: Filter surface area comparisons

Fig 69: Itho filters deform easily

Fig 70: Zehnder small pull tab

7.1.3 Filter comparison - Itho and Zehnder

I bought filters for Itho and Zehnder for comparison. These filters were manufactured by a third party company, but are nearly identical to the original filters, except for an indicator for airflow directon.

The most notable feature of the Itho filter is that it is two filters stacked atop each other. These filters are reversible, which means when one half is dirty, it can be rotated, exposing a fresh area to airflow.

As seen from the Fig. 68 the surface area of half an Itho filter is comparable to that of typical filters. This led me to deduce that the lifespan of this Itho “double filter” is twice that of a regular filter. However, in later stages I found this speculation to be slightly inaccurate.

Zehnder filter feels stiff. There seems to be no apparent difference between G4 and F7 filters. Itho filters feel less structurally sound, and tends to wobble and fold. The markings of the filters are on the top, and difficult to understand. Zehnder filters on the other hand are colour coded, with clear indicators on the front face.

Zehnder filters feel more premium in most aspects, except the length of the pull-tab seems a bit too short. This is likely because from a manufacturing perspective, it is convenient for the bracing to double-up as the pull-tab. Itho filters also achieve this, albeit in a different way, which makes the pull-tab longer, and easier to use.

7.2 | Filter change systems

7.2.1 Zehnder Q450

Zehnder unit filters are angled. An arrow on the front face of the filter indicates which direction should be facing up. This is an effective indication of the correct filter orientation. However, this still relies on the user paying attention to the signage. The filter covers are easily removed, but do not stay attached to the unit.

The manuals for the unit, or the official Zehnder website makes no mention of cleaning filters, only replacing them. Accordingly, there is an indicator on the machine regarding filter maintenance, but it only alerts for filter replacement.[Q450 manual] The customer support of Zehnder advises that filters may be gently vacuumed. [personal communication, appendix] This may lead to confusion.

Fig 71: Filter inserted in Zehnder Unit

Fig. 72: Zehnder Q450 MVHR unit

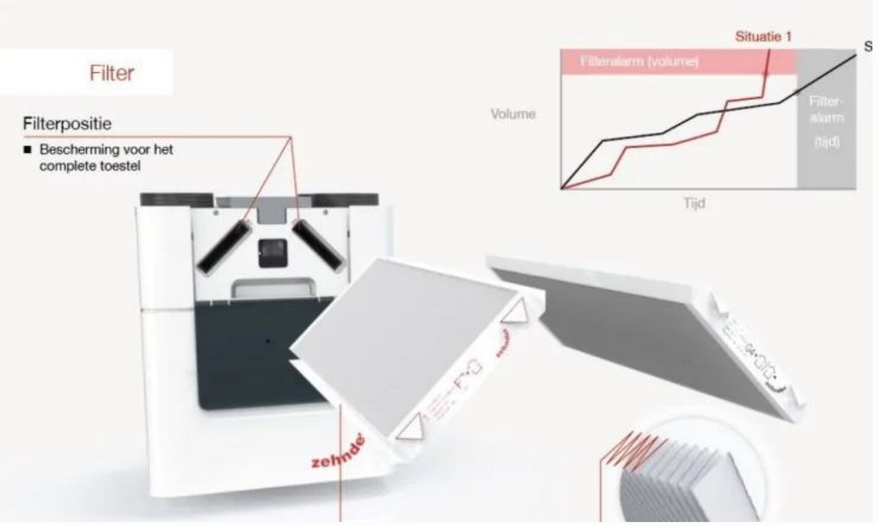


Fig. 73: Filter change Q450

7.2.2 Itho HRU 300

The Itho filter covers are difficult to remove (Fig. 72), and do not stay attached to the unit either. Unlike Zehnder, this unit has separate alert systems for filter cleaning and filter replacement [HRU 300 manual]

The filters enter vertical slots, which makes it difficult to follow the recommended orientation. The slots are also ~~curved~~ on the inside. This makes it difficult to insert the filters. Since the height of the filter is only slightly greater than its depth, it is possible to insert the filters in three possible incorrect orientations out of four.

Fig. 76 and Fig. 77 state assumptions about the machine that I had made for prototyping, that were later corrected.

Fig. 74: Filter dirt patter

Fig 75: Technician in official user guide first attempts to remove the covers with one hand, then uses both hands applying considerable force.

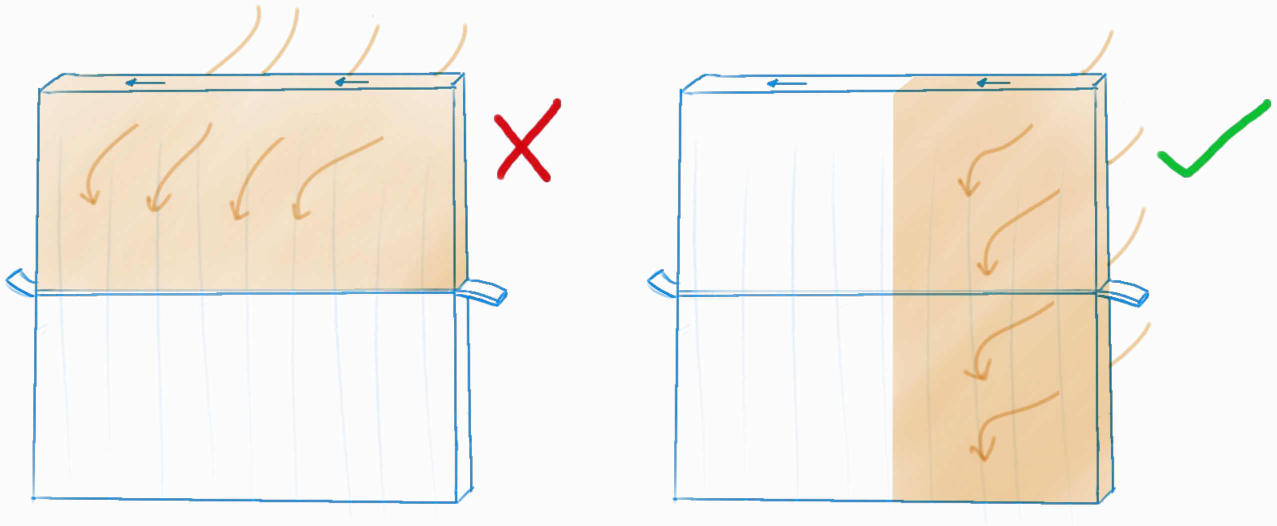


Fig. 76: Assumed airflow zone vs actual airflow zone of ITHO HRU 300 Filter

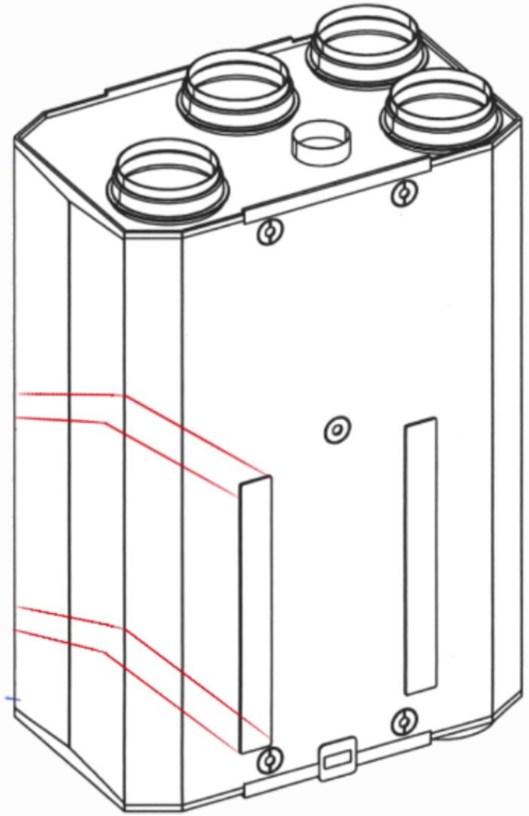


Fig. 77: Bend in machine filter slot. Was discovered to be a sharper bend than initially assumed.

The instructions for reversing the filter in the manual is misleading [fig. 82]. It implies the filters need to be rotated along axis X [fig. 78]. However, this would lead to the filter being inserted with the opposite direction of airflow. The filter needs to be rotated a second time along the Z axis [fig. 79], as shown in the official Itho filter replacement video [fig. 81].

Alternatively, the filter can be rotated around the Y axis [fig. 80]. This axis has the greatest radius of gyration, and therefore is the most difficult axis to rotate the filter around. This may be unintuitive to users.

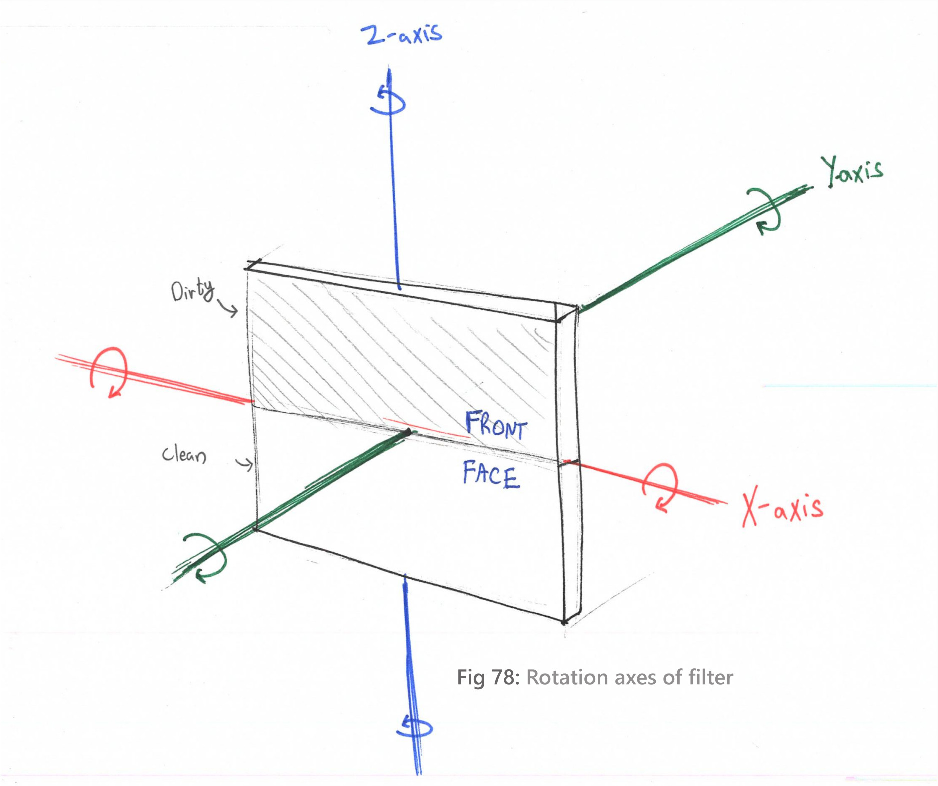


Fig 78: Rotation axes of filter

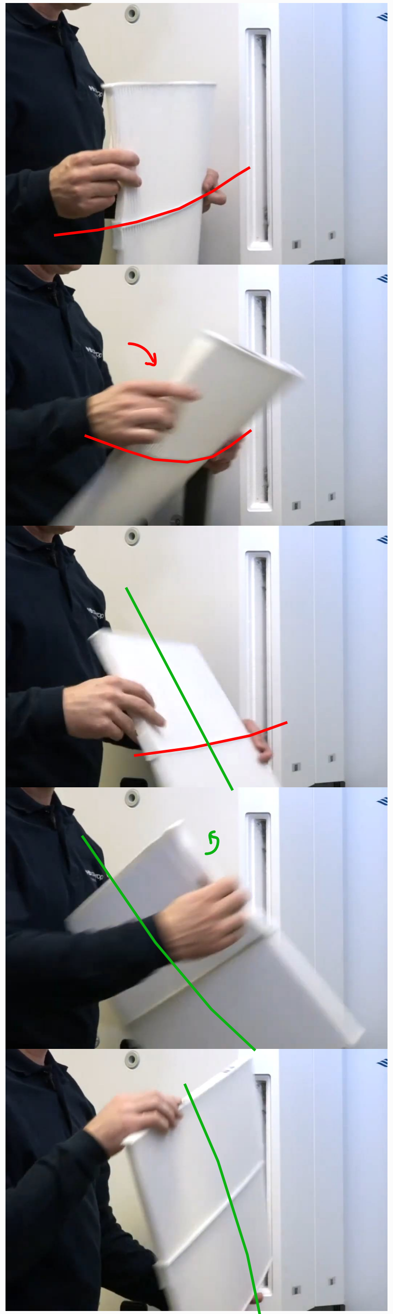


Fig 81: Official Itho filter replacement guide [roughly drawn axes] [source]

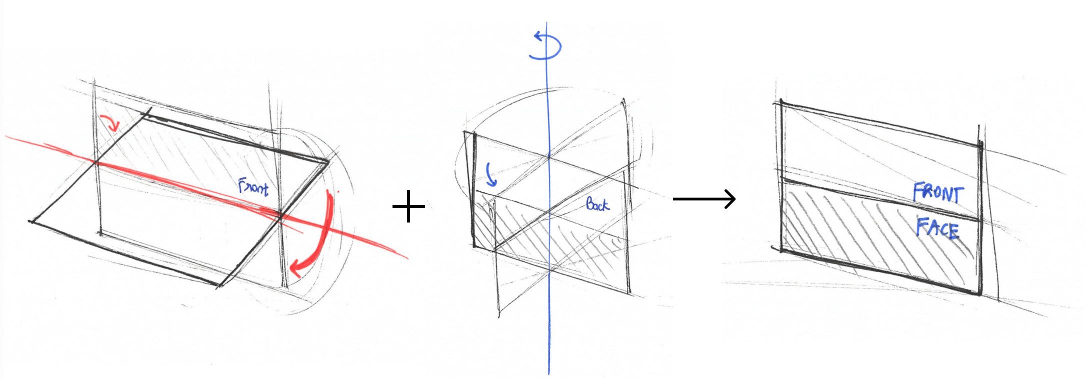


Fig 79: Filter rotated twice for correct orientation

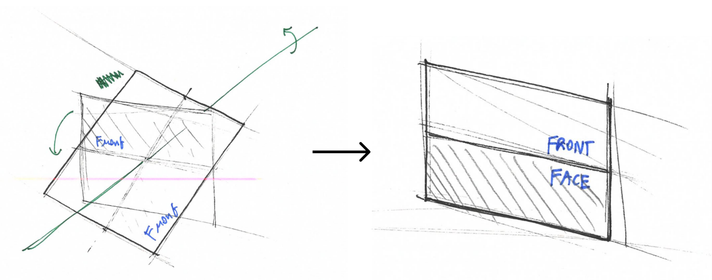


Fig 80: Filter rotated around axis with the greatest moment of intertia for correct orientation

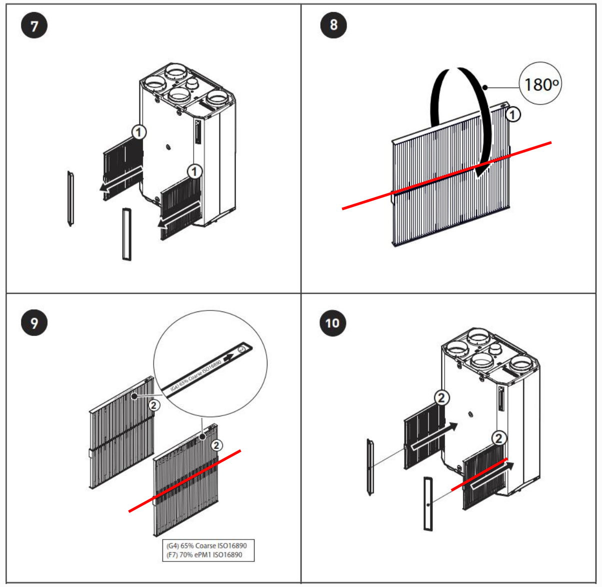


Fig 82: Misleading instructions in official product manual

7.3 | Primary problem areas

7.3.1 Frequency of filter change

From data found online, user manuals and websites of both units, filters are recommended to be changed every 6 months. Filters are expensive, and it would be more desirable to replace filters as part of an annual routine.

Fig X shows the maintenance chart for the Zehnder 450 and Fig Y shows the pricing of filters for popular MVHR Machines (Third-Party)

Part of system	Limit	Responsible	Procedure
Filters	6 months	User	Replacing filters
Valves	6 months	User	Cleaning valves
Grids	6 months	User	Cleaning grids
Controls	6 months	User	Cleaning controls
Condensate drain	6 months	User	Condensate drain filling
Inspection and cleaning system	4 years	Installer or service technician	-

Fig. 83: Maintenance tasks Zehnder Q450 Manual

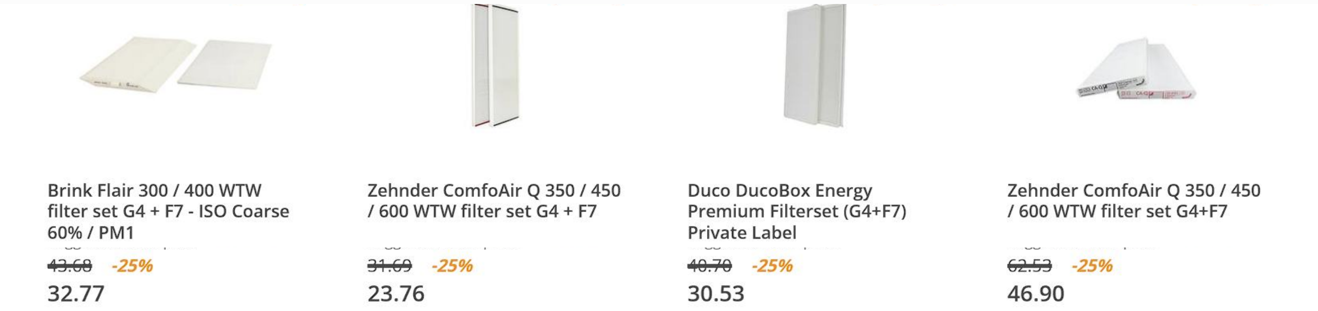


Fig. 84: Typical filter pricing

7.3.2 Physical Strain

Filters, particularly the Itho set are awkward to handle. They have been described as “floppy”.

- I denote the axial deformation of the filter across its yaw axis as bending, and roll axis as leaning.
- The filter does not deform easily under the pitch axis.
- If the filter rolls from one side, torsion or twisting is experienced.

This issue is compounded when vacuuming the filters, causing instability across multiple axes. Lack of a proper area to securely hold the filter from without getting dirt on the hand is another factor that could cause physical strain.

Itho filters were experienced to be difficult to insert back into the unit. This is because the slot is curved, and the filter begins to compress under the force. This is less of an issue when pulling the filter out, since the filter is in tension where it does not deform.

Pull tabs on both filters are not ideal, since they use friction to generate the force. This requires much more force than if a normal force could directly be used. If the filter gets stuck, it may be difficult to remove, and smaller pull-tabs such as on the Zehnder filters may be prone to slipping, especially with oily or grimy fingers.

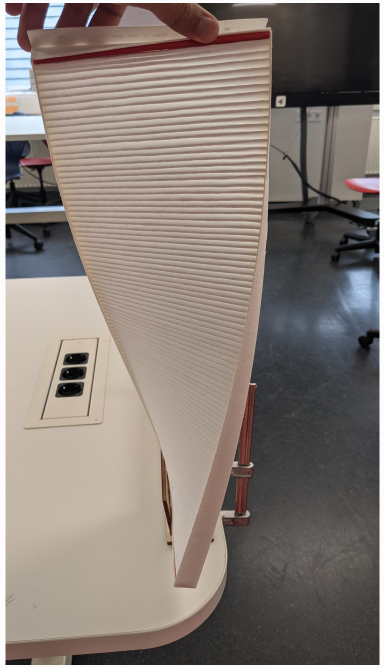


Fig 85: Twisting


Fig 86: Bending

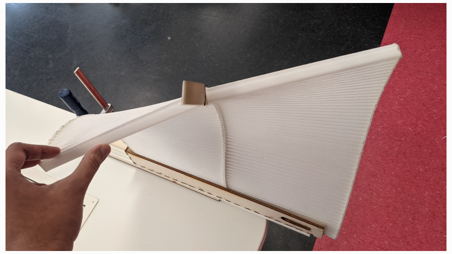


Fig 87: Leaning

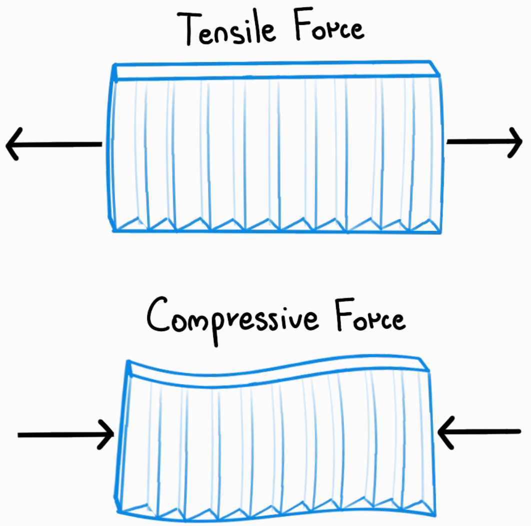


Fig 88: Tensile vs compressive force

7.3.3 Information Deficit

There is a significant information deficit in several key areas related to filter maintenance. First, filter orientation is often confusing, especially with third-party filters that provide excessive information. Important details can easily be missed or overlooked, and the consequences of incorrect filter orientation are not clearly stated, leaving users unaware of potential issues if the filter is inserted incorrectly.

Second, there is confusion around when to clean or replace filters. Manufacturer recommendations can be overly cautious, suggesting replacement even when the filter might still be functional. For example, Zehnder units do not mention filter cleaning as an option in their official documentation, only replacement. However, in email communications, they have acknowledged that vacuuming the filter once is acceptable, adding to the uncertainty.

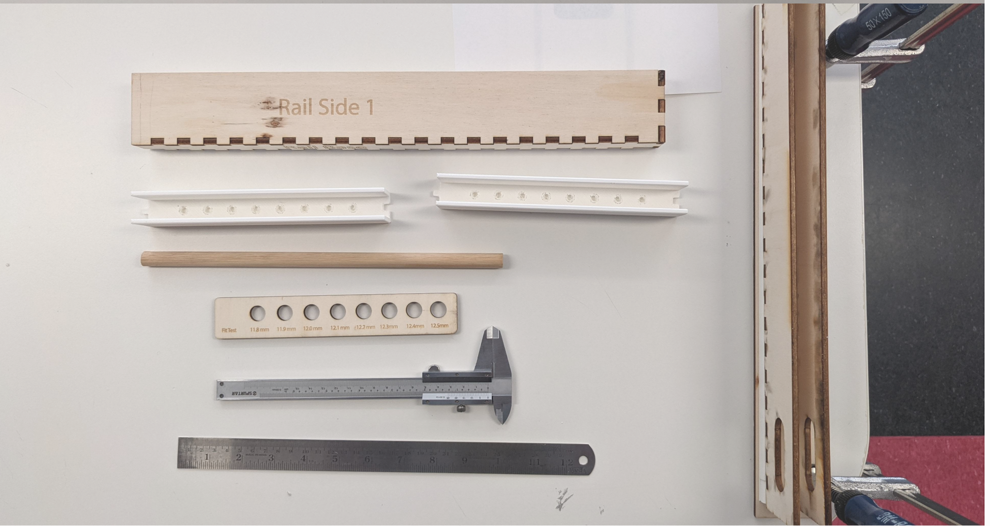
Finally, there is often a lack of clarity about filter grades, such as which filters are G4 and which are F7. Signage on the units or filters themselves may not be clear, making it difficult for users to determine which filter goes where. Users may also be unsure whether they need an F7 filter or if two G4 filters would suffice, leading to uncertainty in maintenance practices.

Key Takeaways

- Recommended frequency of filter change is too high
- Filters are difficult to handle and install, causing physical strain during maintenance.
- There is a lack of clear information on filter orientation, cleaning schedules, and filter grades.

Chapter 6: Conclusion

The chapter identified root causes of issues related to filter maintenance, focusing on information mismatch, physical strain, and the frequency of filter changes. These insights informed the development of retrofit solutions. The next chapter details the concepts prototyped based on these findings.



8. Proposed Solutions

This chapter presents solutions for MVHR systems, highlighting their standardization and the variability in skid construction. Three prototypes, each addressing different stakeholder needs are detailed.

Solution 1: Redesign Filters

8.1 | Redesign Filters

The first solution involves redesigning the filters themselves. This approach is straightforward to implement and incurs minimal additional cost.

While it may not be a complete solution, it adds value for customers and is particularly attractive to third-party manufacturers (TPMs) who can offer a more premium product at a lower price compared to OEMs.

Since I have taken retrofitting as a baseline, the solutions involve the Itho double filter design. The filter redesigns are relatively simple to execute. They are compatible with existing manufacturing equipment, adding minimal operations to the process and provide a minor yet tangible improvement in functionality.

Its features are explained next.

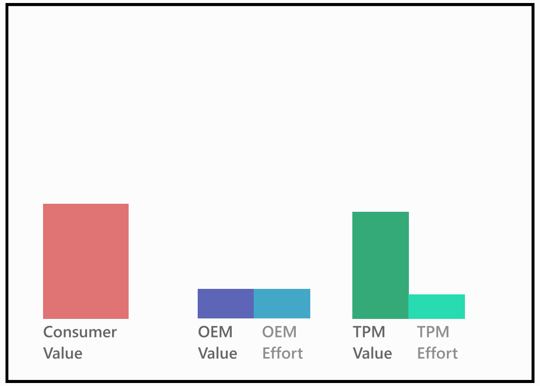


Fig 89: Bar Graph: Redesign Filters

8.1.1 Improved pull-tabs

Pull tabs on filters should be redesigned to avoid use of friction. This can be done in two ways.

The tab is modified into a loop. Since in most filters, the tab is an extension of the bracing, the bracing itself could be looped before assembly of the two filter halves. Alternatively, the loop could be manufactured as part of the glueing operation.

The slot could also be punched from the tab. OEM Zehnder filters already use perforations for the pull tabs [image from official video], so punching a hole could be achieved with a tool change, or even be part of the same operation. [picture/illustration required] This would however, be less sturdy than the loop.

In either case, the loop or perforation can be ignored and be treated as a regular pull-tab if the consumer prefers it.

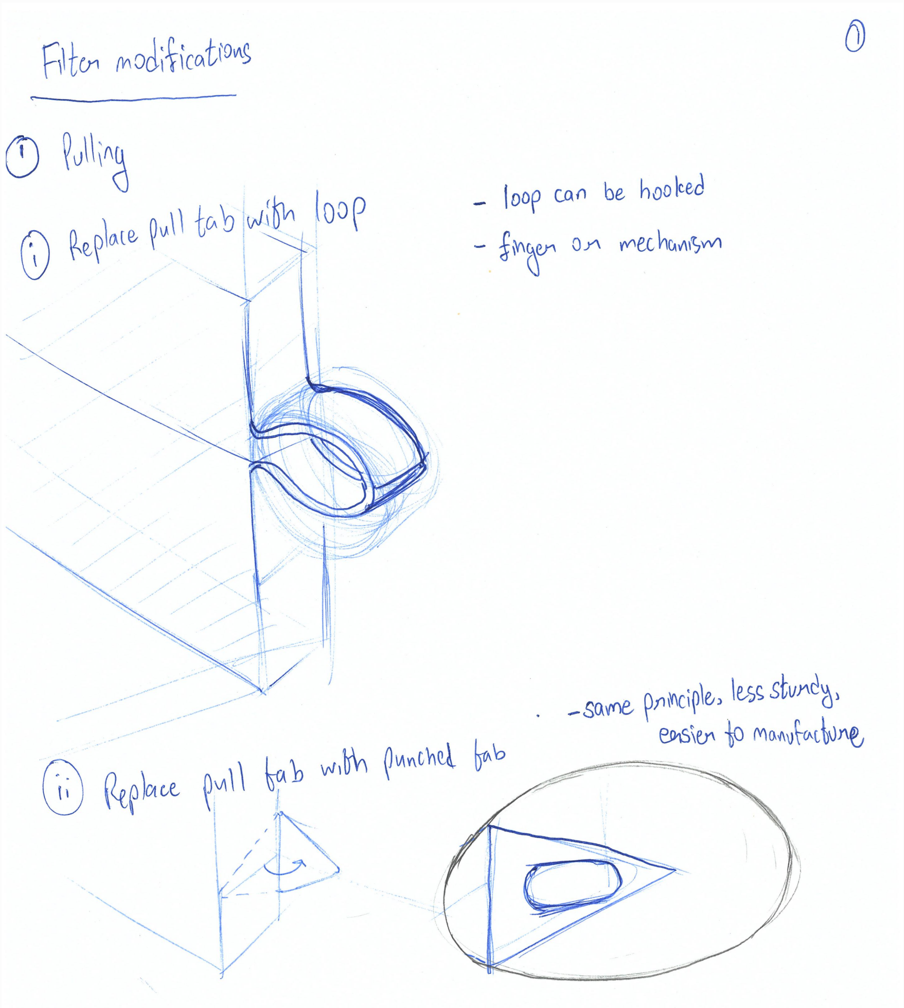


Fig 90: Concept sketch

8.1.2 Reinforcement

Filters could be reinforced. The design of the single Zehnder filters is applied to double-filters.

A stiff bracing at the top and bottom of the filters provides resistance against tilting and bending. [fig. 92] A small strip on the back of the filter provides torsional resistance, reducing the twisting [fig. 93]. As an added benefit, it can be used to more clearly indicate the inward side of the filter (the face without the backing strip faces outwards)

This is a simple redesign, that adds a single additional manufacturing operation to the current Itho filter.

While this reinforcement slightly increases compressive resistance, it is not unlikely to entirely resolve the issue of pushing the filter into the skid.

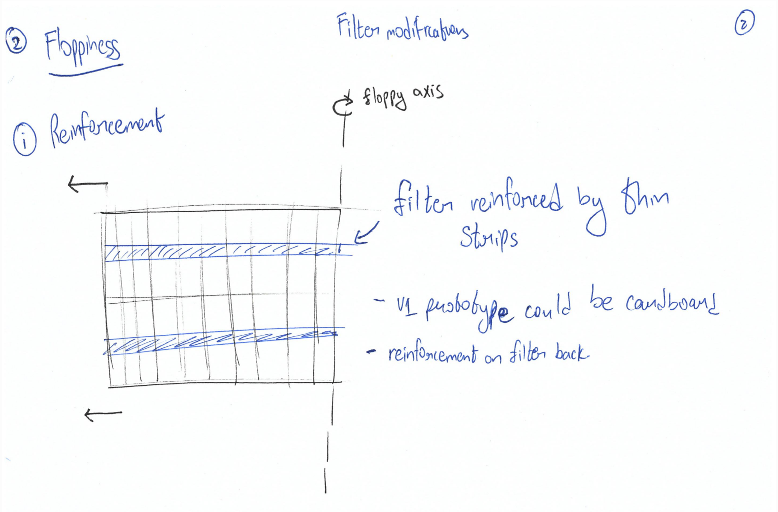


Fig 91: Torsion reinforcement

Fig 92: Original Itho filter torsion test

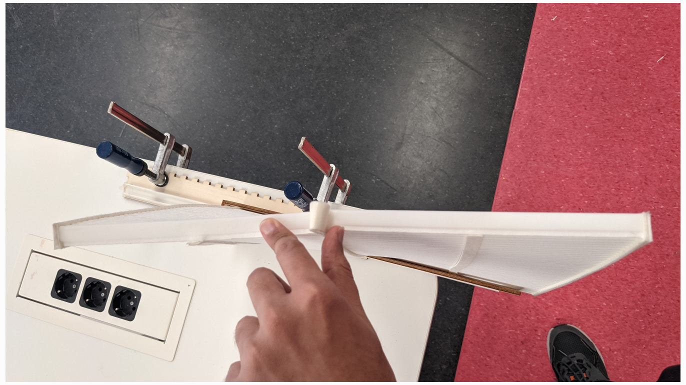


Fig 93: Reinforced Itho filter torsion test

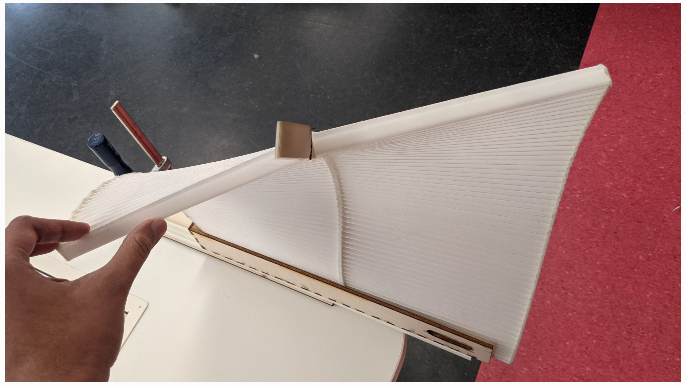


Fig 94: Original Itho filter tilt test

Fig 95: Reinforced Itho filter tilt test

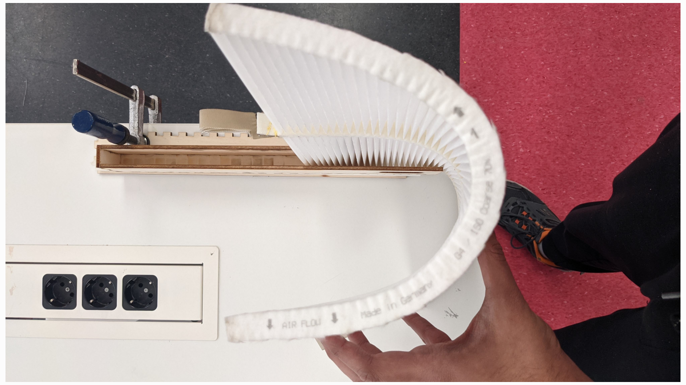


Fig 96: Original Itho filter bending test

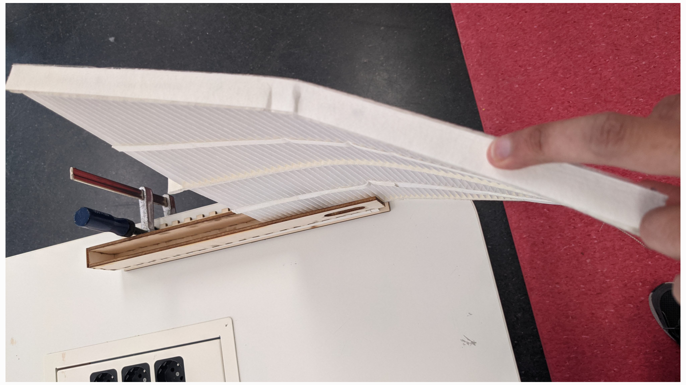


Fig 97: Reinforced Itho filter bending test

Solution 2: Pushrod Attachment

8.2 | Pushrod Attachment

The pushrod attachment addresses the issue by allowing the filter to be inserted under tension rather than compression. This approach is more effective than merely modifying the filter.

The attachment can be implemented by an OEM or TPM and is suitable for filter slots that are not straight. Despite its simple construction and compact design, it requires a modification to the filter and can be complex to use and difficult to install.

Its features are explained next.

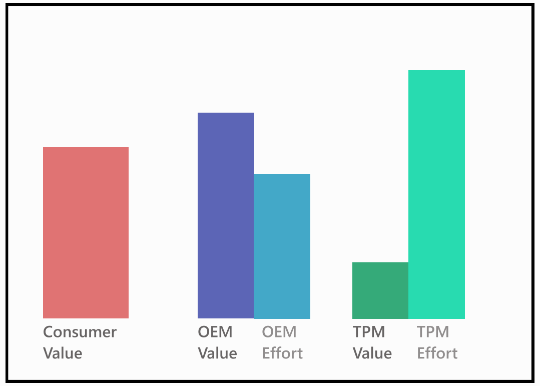


Fig 98: Bar Graph: Pushrod attachment

Fig 99: Detail: mounted channel

Fig 100: Detail: Pushrod in channel

Fig 101: Detail: loop hooked onto pushrod

Fig 102: Tighter loop performs better

8.2.1 Push to Pull

The solution consists of a pushrod that can be hooked into the filter. By pushing the rod, the force vector on the filter while inserting is changed from push to pull.
To take out the filter, pull on the loop, and the rod which is hooked onto the filter comes out as well. Thus, the filter is always in tension, never in compression. Pushrod bypasses the need of compressive resistance.

If the rod and mounting can bend, works for filter slots that are not straight as well.

Fig 103: Inserting filter with pushrod

Fig 104: Pushrod comes out by removing filter

8.2.2 Prototyping

The prototype consisted of 3D printed channels, taped onto a sidewall of the cassette. I drilled a hole at the end of a wooden rod, but not all the way through. Bent a steel wire on a bench vice, and glued into hole.

Demonstrates principle, final solution would be made of very different materials. The channel could be a contiguous injection moulded part, and the pushrod hook would be mounted more securely.

8.2.3 Retrofitting

The pushrod solution is effective for OEMs who can preinstall it on machines before they are sold. It can be added as a small channel on the side, which users can choose to ignore if not needed. Since it does not require design changes, it avoids issues related to regulations or product lifecycle constraints. However, retrofitting this solution on-site is challenging due to the need for precise installation of the channel at the correct height and angle.

8.2.4 Summary

The pushrod attachment is simple in design and can be easily outsourced for manufacturing. It is ideal as a transitionary solution for OEMs before their current MVHR units are phased out. While it doesn't address every issue, such as improving the ease of vacuuming, it effectively resolves several other problems related to filter insertion and orientation.

Fig 105: Prototyping loops and slots for pulling

Fig 106: Steel wire bent into hook on vice

Fig 107: Using hand drill for hole since wood is very soft

Solution 3: Rail System

8.3 | Rail System

The rail system is the most comprehensive solution, offering the greatest return despite its complexity. It uses a bracket mounted on rails to allow the filter to slide in and out. This system does not require any modifications to the filter, making it compatible with any TPM filters. It can be sold as an add-on and is feasible as an on-site retrofit.

Its features are explained next.

8.3.1 Sliding bracket

The filter is inserted into a sliding bracket made from rigid material. This bracket is moved in and out on a rail system, allowing the filter to be repositioned without direct contact and avoiding structural issues. When extended, the bracket stands independently, freeing up both hands for vacuuming. The filter is then slid back into place once maintenance is complete.

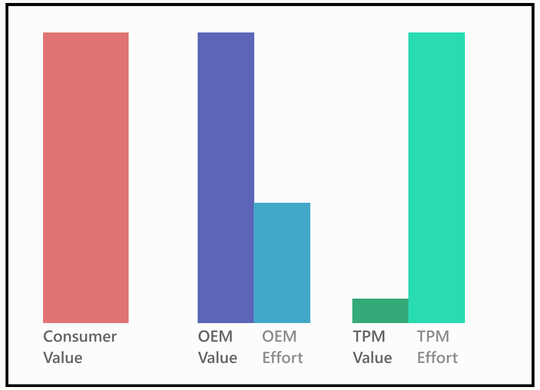


Fig 108: Bar Graph: Rails system

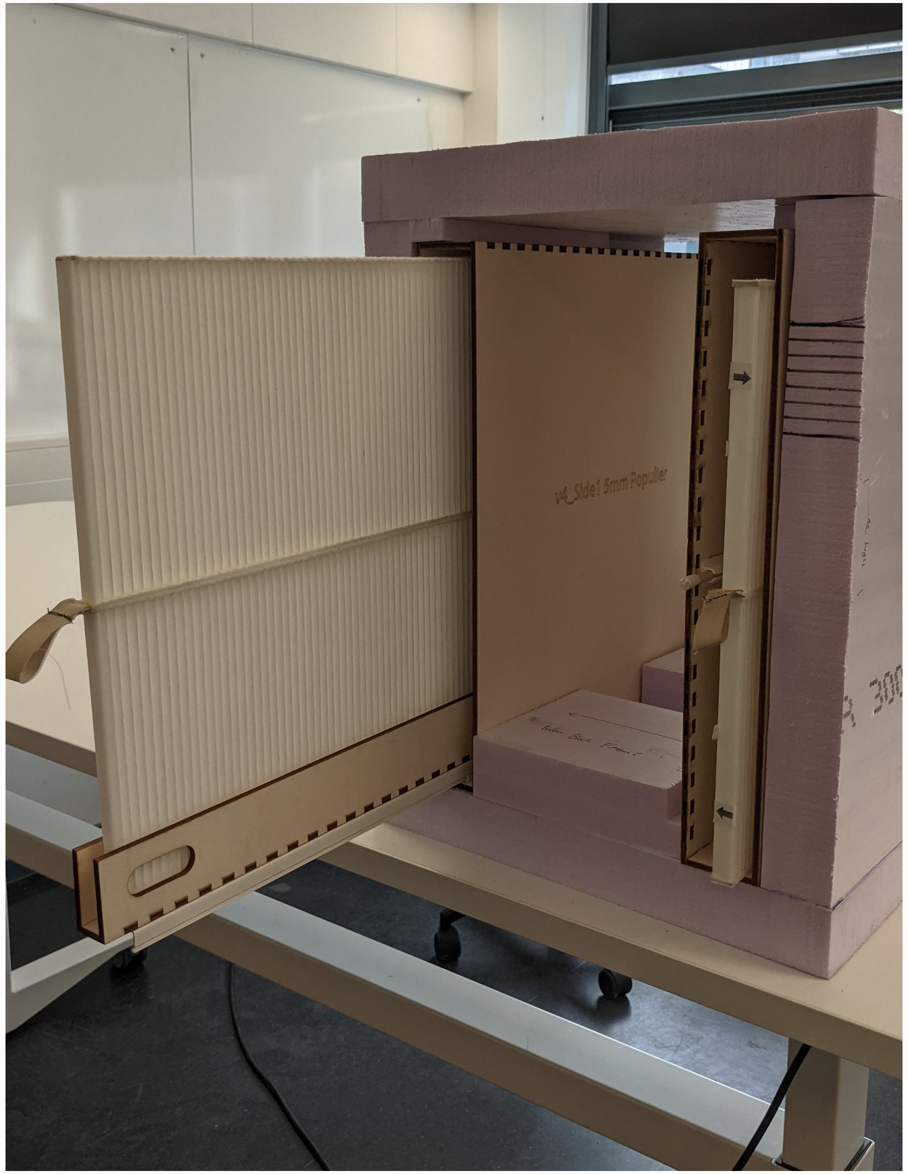


Fig 109: Sliding rail system

8.3.2 Prototyping

Prototypes of the brackets were lasercut from 5mm populier wood. I used plastic wire ducting as rails. Additionally, finger slots were added to the final version of the brackets.

I built a test rig and clamped onto the table to test the motion of the bracket on the rails. Based on the findings, the final prototype used wider ducting and flipped the ducting upside down to allow for more stability in the fully extended position.

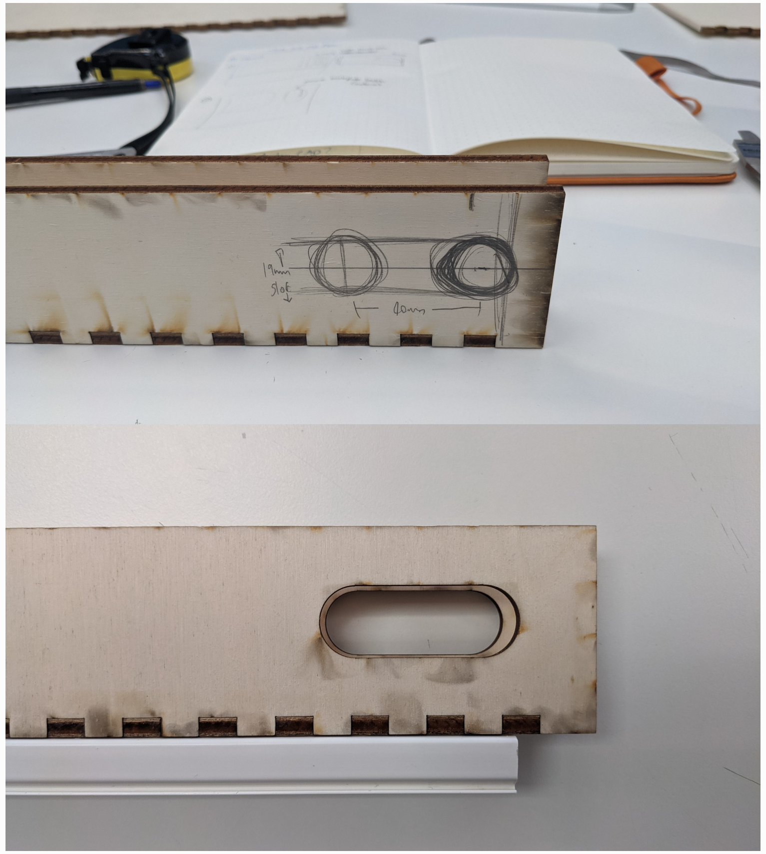


Fig 110: Initial and final prototypes of bracket

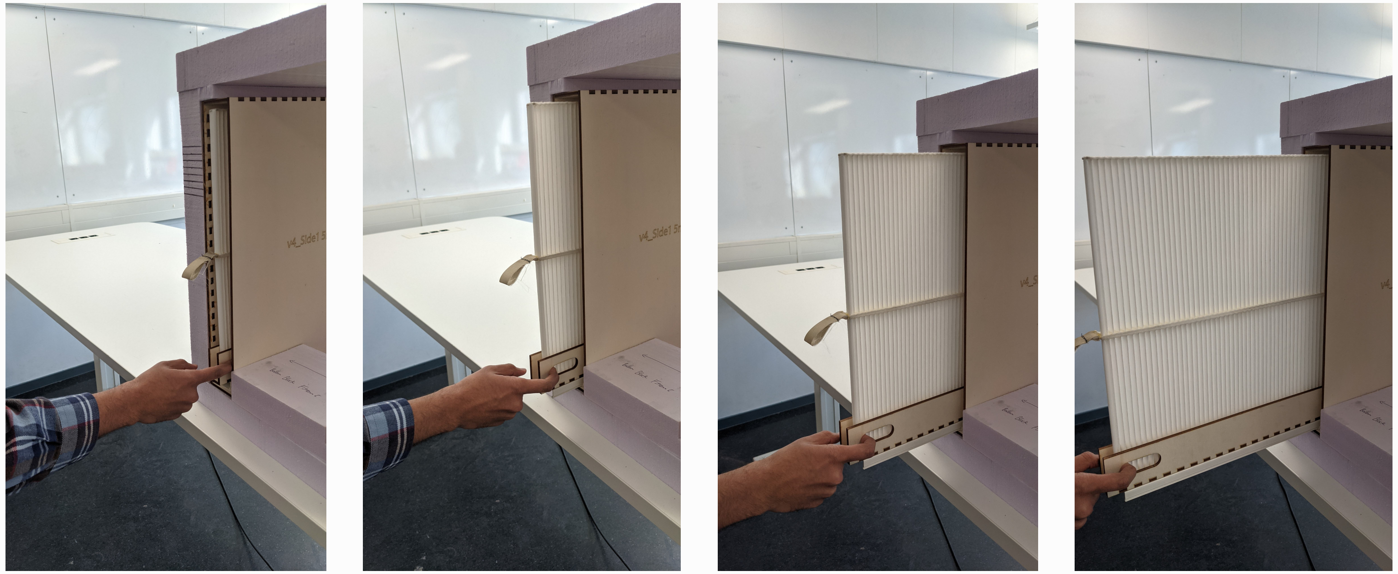


Fig 111: Taking out filter for cleaning or replacement

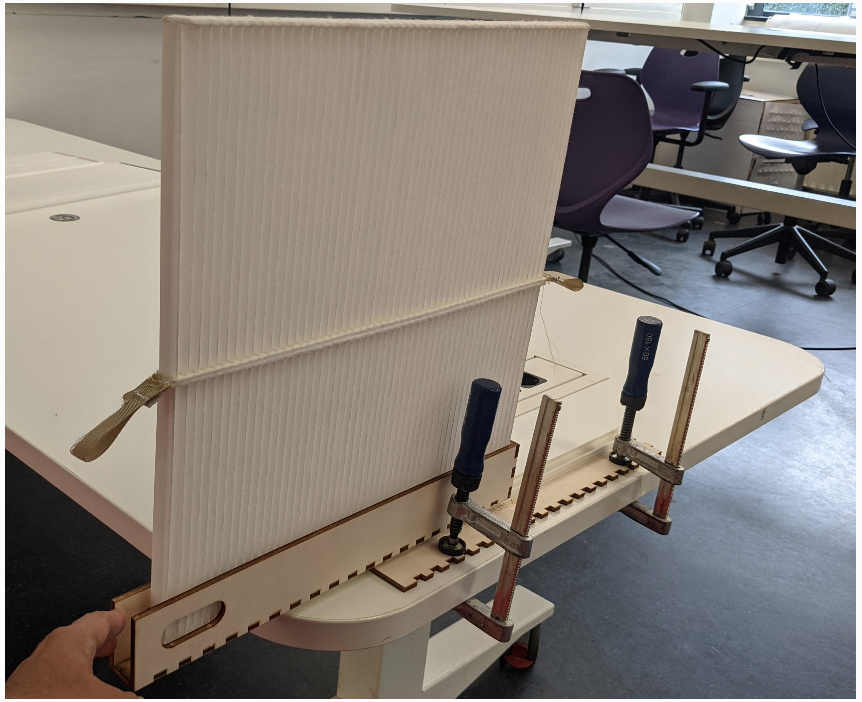


Fig 112: Testing setup for rail system

8.3.3 Redesign details

The brackets and rails could be manufactured using injection molding for precision and durability. To prevent the bracket from detaching at full extension, an end stop could be incorporated. Pre-installing rail channels in all units would not impede use even if no bracket is present.

However, this system is less effective for non-straight slots and may require more complex solutions, such as wall-mounted systems or articulated brackets with curved guides.

Future improvements could include a tilt mechanism to enhance filter access when fully extended and asymmetric tab extensions to ensure correct filter orientation and airflow direction. Additionally, the bracket design could be optimized for better ergonomics.

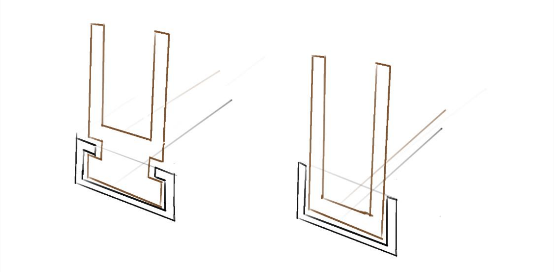


Fig. 113: Bracket-rail potential shapes

Summary

The rail system demands significant design effort but effectively addresses most issues, providing substantial value for the customer, if it is compatible with the existing machine.

It has the potential to reduce maintenance costs by preventing expensive breakdowns. The brackets can be easily replaced if damaged. The system greatly simplifies cleaning by allowing filters to be vacuumed without direct handling.

Since it requires no modifications to current double-filters, it ensures compatibility with third-party products and avoids the need to update the filter manufacturing process. However, implementing this system in non-straight ventilation slots poses challenges.

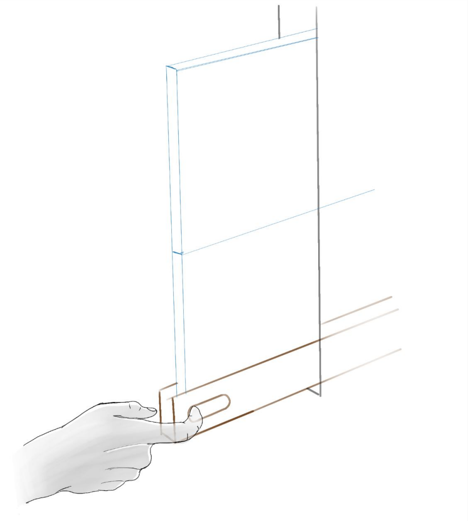


Fig. 114: Finger slot to pull

Fig. 115: Integration of rail system in machine

9. User Testing

This chapter presents the user testing of prototypes, involving in-depth testing and observation of all proposed solutions with the same residents from Chapter 3. The aim is to assess the effectiveness, usability, and overall experience of the solutions, providing direct feedback from the end-users.

9.1 | User Testing

The testing was conducted with the same residents from the earlier observation visits, which was advantageous as the context was already established, and we could get straight to the specifics. The user test was divided into three parts

First I observed the machine and filters again, making use of my improved understanding of the system as compared to the initial visit. I quickly tested any hypotheses I had, validated or invalidated assumptions, and adjusted the subsequent user tests accordingly. I then assessed the state of the filters, asking residents questions about them.

Next, the filter prototypes were tested. I observed how the residents interacted with the ventilation system in depth. They removed, rotated, and inserted filters multiple times, following different instructions and using various filters, including the original ones and two of my modified versions. I compared their interactions with all the filters.

Finally, the MVHR prototype was tested. I placed it at a height and asked the users to replace filters using both the pushrod and rails prototypes. They were instructed to perform the tasks slowly while verbalizing their thoughts. I also observed other small interactions during this phase.

9.1.1 System Observations

Here are the observations about machine and filters I learned during the visit and their consequences.

I discovered that the airflow zone is through the front half of the filter, rather than the top half as initially assumed. This was surprising, as it feels unintuitive for air to flow through only half of each individual filter in the double filter system. Based on this insight, I adjusted my demonstration of the rails prototype to accommodate this airflow orientation. With this understanding, the filter does not need to pulled all the way out to be vacuumed.

To confirm the airflow direction, I attached a piece of masking tape to my finger and inserted it into the filter slot while the machine was running. This practical test validated my assumption that air from both filters flows toward the center of the unit.

The cover was difficult to remove, though this was a known issue that has already been addressed in subsequent models.

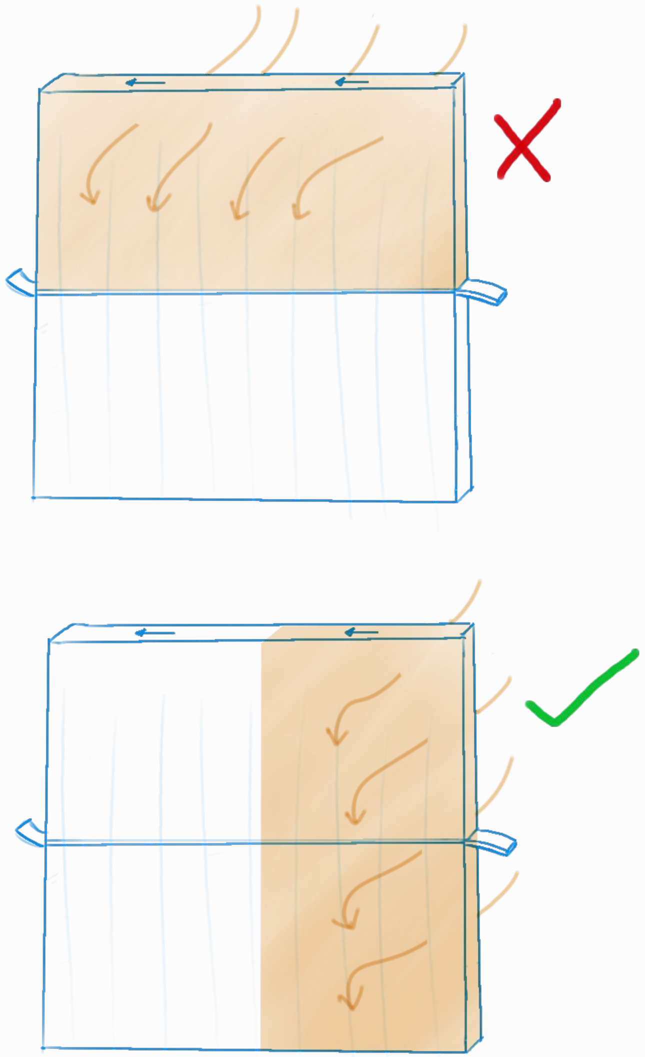


Fig. 116: Correct direction of airflow as observed

Upon visual inspection, I discovered that the filter slot was not gently curved as I initially expected. Instead, it was mostly straight with a sharp bend towards the end. This would make stiffer filters difficult to enter.

The installation height of the MVHR units varied between the two apartments, with Resident A's system positioned 30cm higher than Resident B's. This indicates that the packaging constraints for the MVHR system are not very strict. As a result, my designs must consider the possibility of shorter users needing to access a higher-mounted MVHR system.

Third-party filters (TPM) were less stiff compared to the original Itho filters (OEM). OEM filters featured shorter pull-tabs and lacked airflow direction markings, unlike TPM filters. Initially, I hypothesized that pleated filters had a directional nature based on TPM markings. However, this hypothesis was later proved false, though did not impact the user test results significantly.

In both apartments, Maintenance Companies had replaced the filters incorrectly. Resident A had two F7 fine filters instead of a G4-F7 pair, while Resident B had two G4 coarse filters. Additionally, none of the units had filters that were installed according to the indicated instructions.

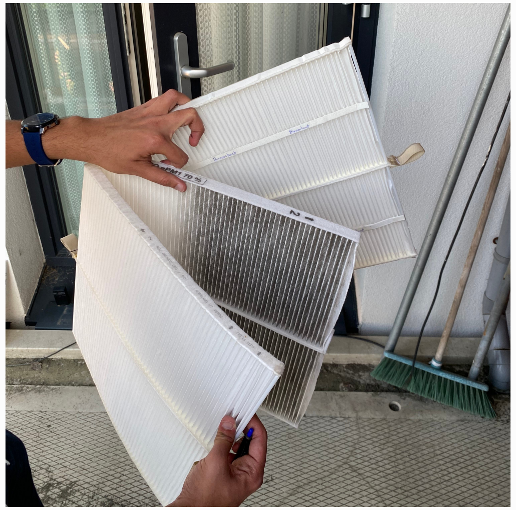


Fig. 117: Three filter variants tested

Fig. 118: Filter inserted in the wrong direction

Fig. 119: Both filters are coarse and inserted in the incorrect orientation according to the indicators

9.1.2 Filter modifications

One of the filters was reinforced on the top, bottom, and sides. Both users disliked this reinforced filter, finding it too stiff and difficult to bend when fitting it into the slot. My previous tests suggested that the stiffness was primarily due to the reinforcement on the top and bottom of the filter. Unfortunately, these reinforcements couldn't be removed, but I confirmed this hypothesis by removing the backing strips from the sides and asking the residents to try again. No noticeable change was observed, supporting the theory that the side backing strips do not significantly affect the filter's bending.

The second filter had its top and bottom strips reduced in width from 23mm to 15mm to fit the bracket in the rail prototype. When tested, users preferred this thinner filter over the original, finding it easier to insert and remove.

Users frequently overlooked indicators on filters during changes and found the instructions difficult to understand. To address this, I added a label reading “binnenkant” (Dutch for "inside") to the backing strip of the stiff filter. This straightforward indicator proved easier for users to follow compared to the original arrows indicating in/out.

When users were instructed to rotate the filters as they thought best, neither filter was rotated correctly. Informal tests with university colleagues produced similar results, with users rotating the filters in random directions.

When the filter is inserted, it conforms to the shape of the bent filter slot. It becomes hard to insert when rotated, because the filter then bends the other way. To fit it smoothly, I had to roll it back in the opposite direction.

Residents were vaguely aware that the system should be shut off while changing filters but neither turned it off when changing filters.

User A ignored the filter loop, finding it unnecessary and instead grabbed the entire filter directly. User B used the loop to pull the filter out slightly before grabbing it. While the loop is not as critical as initially thought, it remains useful if implemented at low cost. Users sometimes used the loop as a pull-tab. Grabbing the full filter likely easier but it can get dirt on the hands.

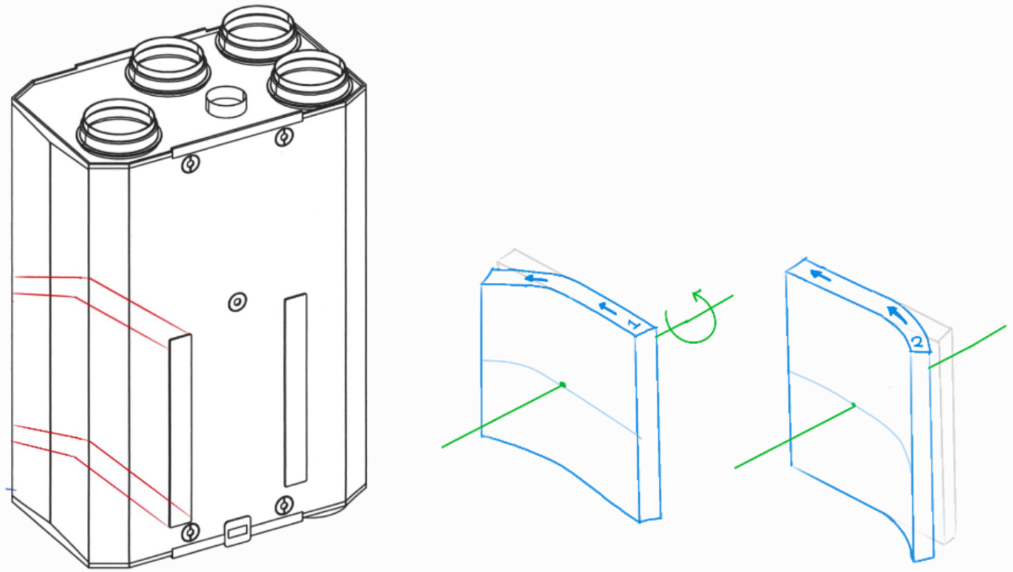


Fig. 120: Filters tale shape of the slot, making them difficult to insert when rotated

9.1.3 MVHR Prototype

The test procedure involved placing the prototype at a height similar to that of the skids. Users were instructed to slowly remove, rotate, and reinsert filters for both solutions, while verbalizing their thought process. Note that the prototype featured a straight slot and provided slightly more clearance than the actual machine, which may have influenced their perception.

Pushrod Mechanism

Users found it difficult to intuitively understand how to use the pushrod mechanism. They experienced resistance with the rod due to friction and tolerance issues between the channel and the rod. In some cases, users would pull out the filter using the rod itself. The rod could be made flush with the channel, so it would not be possible to pull out the filter. Another issue noted was the rod falling out during use.

The length of the loop presents its own set of problems. A smaller loop allows the hook to go all the way in but requires the hook to be positioned at the far end. A larger loop provides more leeway but requires manually pushing the filter through the bend, which is the main problem. An alternative locking mechanism, such as clip-ons used in document folders, could be considered to replace the hook.

Alignment issues could arise during retrofitting if the system is not level, potentially causing the rod to skew. It might be beneficial to replace the rod with a flat plate, ideally positioned at the bottom. The pushrod ended up worse at retrofitting than initially thought.

Despite these challenges, the principle of converting tension to compression remains valid and could be useful. However, the pushrod prototype was generally disliked by users and was found to be too “fiddly,” making it less desirable as an option.

Rails mechanism

Airflow direction is through the front half of the filter, not the top half as previously assumed. This insight necessitates a redesign of the system to accommodate the new understanding of the air channel. The new bracket design could feature a taller back half and a shorter front half to avoid obstructing airflow.

Both users initially overlooked the rails and simply pulled on the filter, causing it to slide off due to excessive clearance. Reducing the clearance in the final version could address this issue.

Users find the rail action satisfying. User B prefers the rail system, while User A sees its potential benefits, particularly for vacuuming, even if they do not personally need it for changing filters. An endstop is required to prevent the bracket from sliding off, or alternatively, the system could allow full sliding but must be easy to realign.

Inserting the filter into the sliding bracket poses another challenge. If clearance is reduced, provisions should be made for inserting the filter from top to bottom to avoid compression during sliding.

Initially, a tilt mechanism was considered for the filter, but user tests and machine inspections indicated that it is unnecessary.

For sharp bends, the rails could potentially allow the filter to jut out the back, which might help secure it and follow the bend. An asymmetric filter design could ensure fixed orientation with the rails. The rails system shows promise as a retrofit solution, possibly better than anticipated. It could be a great solution for hands-free vacuuming, as only half of the filter needs to be exposed, which should fit within skid clearance.

Key Takeaways

- Recommended frequency of filter change is too high
- Filters are difficult to handle and install, causing physical strain during maintenance.
- There is a lack of clear information on filter orientation, cleaning schedules, and filter grades.

Chapter 6: Conclusion

The chapter identified root causes of issues related to filter maintenance, focusing on information mismatch, physical strain, and the frequency of filter changes. These insights informed the development of retrofit solutions. The next chapter details the concepts prototyped based on these findings.

10. Evaluation and Final solutions

This chapter presents the background of some key stakeholders that were interviewed and introduces the final ten principle solutions. These solutions, primarily aimed at manufacturers, have been validated by this stakeholder to ensure their relevance and feasibility. Through these interviews and validations, the chapter establishes the context and rationale behind the proposed solutions, bridging the gap between user needs and technical implementation.

10.1 | Stakeholder Evaluation

After user testing, I conducted some validations with different stakeholders. However, note that these experts by nature will have their own biases, and some information will be contradictory. In the next chapter, I will present my final suggestions based on my evaluation of the different stakeholder's viewpoints. In this subsection, I present each major stakeholder interviews and a few key insights from each

Tim Ivangh, Engineer, Itho Daalderop (Manufacturing company)

Tim was incredibly helpful throughout the process, offering in-depth knowledge of the HRU 300 MVHR unit. During the first interview, I was able to validate many assumptions. For instance, I discovered that the double filter design was not intended to increase filter lifespan, but rather resulted from the need to make the machine more compact.

Another important insight was that the direction of airflow on the TPM filters is not an accurate indicator. These pleated filters are unidirectional. In Zehnder filters, directions are marked to create a better seal with the system, while Itho filters are marked so that the dirty side does not face inward during rotation.

Tim also explained the manufacturing process of the filters, as depicted in Figure 121. The filter material is rolled into pleats, and then the top and bottom bracing, along with the pull-tabs and the second filter, are manually glued. This information made the proposals more meaningful by grounding them in the practical realities of manufacturing.

A second interview was conducted with Tim to validate the final proposals, ensuring their feasibility and relevance.

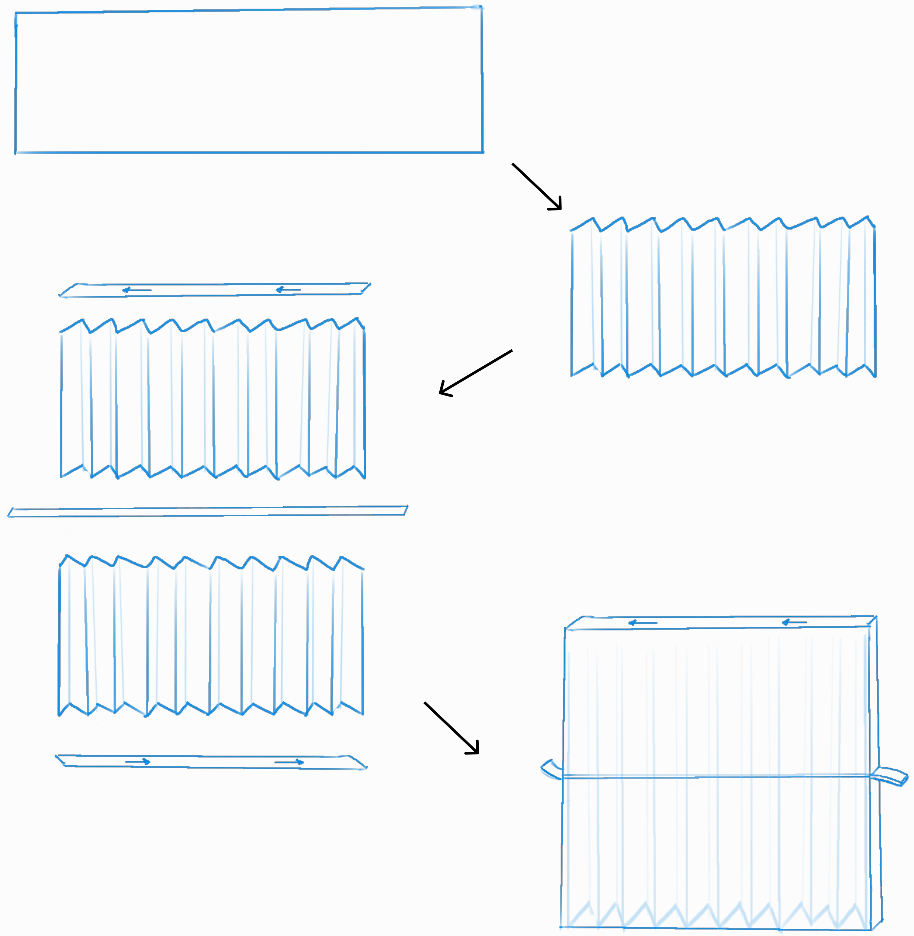


Fig. 121: Manufacturing process of Itho filter. Pleats are made from filter material, which is then cut, and glued with backing strips and a pull-tab to make the final filter. The manufacturing of most MVHR filters follows a similar pattern.

Eric van der Voort, Senior Designer, MMID (Construction Company)

Eric provided valuable insights during our collaboration, particularly regarding the technical feasibility and practical considerations of the proposed solutions. Having worked closely with Bosch Nefit on the construction of skid-based housing projects, his insights were instrumental.

He emphasized that while retrofitting is generally difficult, it is certainly possible and can hold significant value for housing corporations. A single-time retrofit could be strategically combined with standard maintenance operations to reduce the number of maintenance calls. He also noted that it would be beneficial if the retrofit did not require major disassembly for the machine.

Regarding the rail system, Eric highlighted a potential issue with moving components, particularly sliding components that are positioned in the path of airflow. These components might get clogged over time, which could affect their functionality. We confirmed that the brackets could be manufactured by injection moulding.

Overall, Eric found the suggestions to be plausible, provided that the cost implications are carefully managed.

Patrick C, the Director of Heat Space and Light Ltd (Building design consultancy,)

Patrick, the director of a UK-based low-energy building design consultancy, provided valuable technical insights during our brief 20-minute interview. Although his focus is on homeowners, his experience with MVHR systems, especially Zehnder machines commonly found in both the UK and the Netherlands, made his input relevant to my project.

One of his key recommendations was that filters in MVHR systems should definitely be vacuumed to remove large visible debris, such as fruit flies, insect parts, and airborne seeds. He explained that gentle vacuuming should not damage the fibers and can effectively remove coarse particles larger than 10 microns. This advice aligns with my understanding of filter maintenance, particularly for large debris

Patrick also suggested that manufacturers might be overly cautious with their six-month filter replacement recommendations. In his experience, a one-year interval is usually sufficient for filter replacement. He also noted that while clogged filters can increase power consumption (potentially doubling it), the overall energy usage remains relatively low, around 0.5 kWh/day. Importantly, he pointed out that clogged filters are unlikely to cause damage to the MVHR machines themselves.

Davide Polverini, Policymaker, European Commission (Government)

Davide Polverini, a policymaker with the European Commission, primarily focuses on the Right to Repair policies. Although I couldn't arrange a direct interview with his colleague in the residential filter policy department in time for the completion of my thesis, I still gathered valuable insights and resources for future exploration. This interview could be a key opportunity to dive deeper into the policy side of residential filters, manuals, and machines, particularly in understanding any upcoming regulations that may impact the sector.

One interesting insight Davide provided is that policy can only exert control up to the point of product sale, but not beyond that. For example, while regulations could dictate the design and lifespan of filters, they cannot impose requirements on how filters should be cleaned or when they should be replaced by consumers. This limitation highlights a significant gap in policy impact on long-term product maintenance and user behavior, which would be an interesting area to explore in a future study.

10.2 | Advice to Manufacturers

The final solutions offer principled advice tailored for Original Equipment Manufacturers (OEMs) of Mechanical Ventilation with Heat Recovery (MVHR) systems. It's important to note that not all proposed principles need to be implemented, and some solutions might be mutually exclusive. The optimal set of solutions will depend on the specific circumstances of each case.

OEMs wield considerable control over both the ventilation systems and the filters. The following insights highlight key areas for OEMs to address, along with additional suggestions where applicable.

These recommendations are crafted as practical advice for integrating improvements into existing skid systems used in large social housing apartments. The focus is on retrofitting, and the implementation of these changes is analyzed in detail.

All suggestions have been validated by Tim Ivangh from Itho, ensuring their relevance and feasibility for OEMs.

10.2.1 Improve user manual

Principle: Provided information must be comprehensible, accessible, and complete.

- Current user manual does not properly convey relevant information, reading to knowledge gap between end-users and manufacturers. Some instances and how to resolve them are given below.
  - Filter rotation diagram is misleading. It shows a rotation in the wrong axis, but the text mentions the correct direction of rotation. Procedures, especially those involving residents should have clear diagrammatic representations.
  - Information about filter grades, which filter should go where, procedure for vacuuming filters, is missing or hard to find in the manual or website. This information should be provided in the chapter for which it is relevant.
  - Giving the reasoning behind certain instructions would help users understand the system and follow instructions better. For instance, the section that mentions that power to the MVHR unit should be turned off while changing filters should mention that this ensures accumulated contaminants not get sucked into the machine. Similarly, reasons for why filter orientation is necessary would be helpful.
  - The manual should have a visual checklist for residents to check if the machine has been installed properly. It could include the correct orientation an grades of filters, an indication of how the ducting should look, etc.
  - Implementation: Update the digital manual or create an improved user guide

10.2.2 Alternative power-off method

Principle: Powering-off unit should not cause physical strain

- ITHO HRU 300 manual mentions power supply should be cut by pulling out plug or depowering system. No alternative ways of depowering system are mentioned in the section
- There are in fact no alternative power-off mechanisms in the machine [source: Tim]. I believe that the plug is too difficult to remove, and neither the user or maintenance crew is going to put in that effort. If a task has a high barrier of entry, end-users will cut corners.
- Power-off is necessary, as not all impurities stick to filter. Some may fall off. If airflow is on during filter change, large particles such as insect parts may find their way into the heat exchanger.
- A switch cannot be the solution, as MVHR must run 24/7 and that would incentivise users to switch the system off a lot more often due to problems such as noise.
- A possible solution is a 10-minute shutoff timer that can be activated when the input for filter change is made. This is something that already has to be done, and the solution can be implemented through a software patch.
- Implementation: Could be easily bundled with a software update, at next to no cost.

10.2.3 Improved Indicators

Principle: Indicators on components should be clearly visible and recognisable

- When the filter is in the ITHO machine, the indication is hidden because it is on the top.
- An indicator should be present on the front face, so it is visible even when the filter is fully inserted.
    - For the Itho filter, it may not be possible to directly print the indication on the front face, since it is an exposed filter pleat. However, the top/bottom strips can be extended and folded to achieve the same without adding an extra process.
- Indicators on the side could be easier to understand and more visible while handling.
    - An indicator that says “binnenkant” or “inner side” could be added to a reinforcing backing strip for no additional cost apart from adding the strip itself.
- TPMs must be careful to not add unnecessary information that may be conflicting or confusing, such as the airflow direction indicators found on third-party Itho Filters
- Coarse (G4) and Fine (F7) should be colour coded. If that is not possible, a unique hatching pattern could be used to identify each skid.
- The manual should include a clear diagrammatic indication that G4 filters should be used on the machine side, and either G4 or F7 for the outside. This indication could also be pasted onto the machine, so users can visually check if they have the correct filters without having to check the manual.

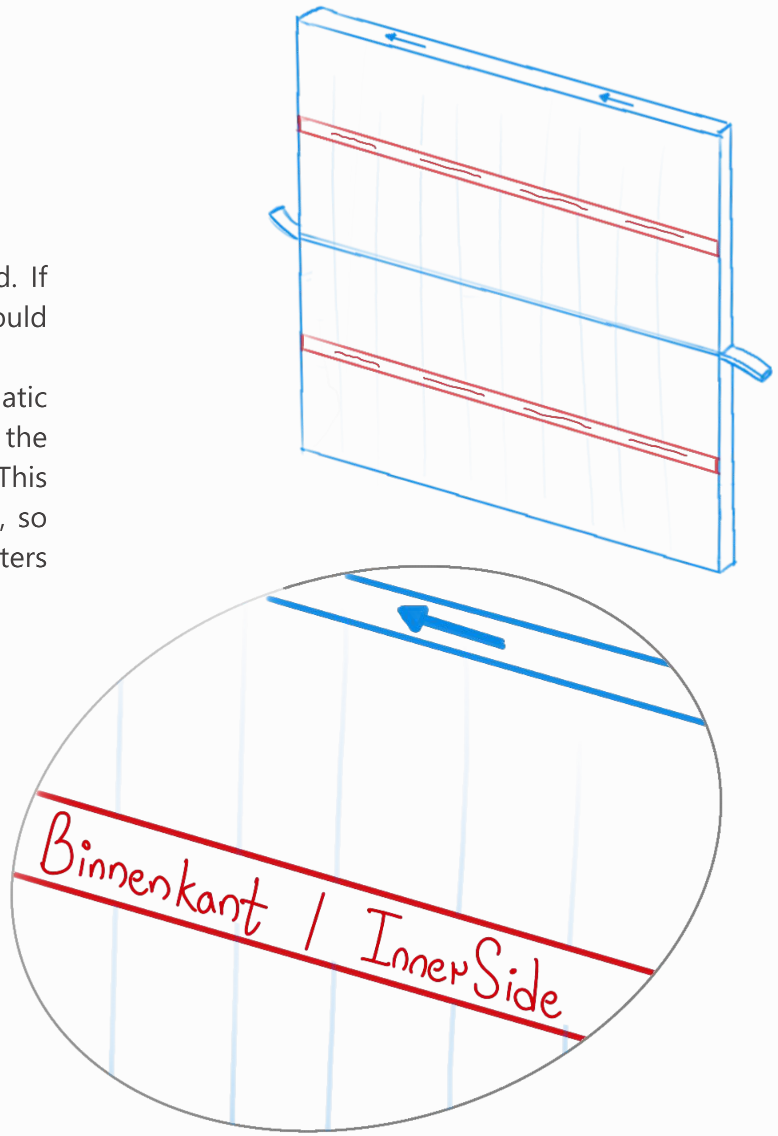


Fig. 122: Labelling on the reinforcing strip indicates the inner side.

10.2.4 Improve filter handling

Principle: Filter should resist compression, have sufficient clearance with slot, and should provide sufficient grip.

- By resisting compression, the filter is less likely to deform when inserted into the machine. This can be accomplished by means of a backing strip added to one side of the filter.
  - This imparts greater torsional stiffness and compressive resistance, while still allowing for the filter to bend.
  - Since the all the strips are manually glued, this adds two operations to process, costing an additional 75 cents per filter (Ivangh, personal communication, August 2024).

- Narrower filters are easier to insert and take out.
  - Current width of the filter strips are 23mm, which are glued to the top and bottom of a 15mm wide pleat. This width could be reduced by a few millimetres (Ivangh, personal communication, August 2024).
  - This is unlikely to cause any increase in manufacturing cost once the appropriate new width is determined.

- A pull loop allows for the filter to be pulled out more easily. Users with long nails for instance, can slide their finger into the loop and pull using normal force. Whereas with pull tabs friction is used to pull out the filter, which requires more force, and can cause fingers to slip.
  - Residents can use the loop as a pull-tab as well if they do not prefer it.
  - Since the filter strips are glued-on, the strip in the middle can come witha premade loop, making no change to the process and adding negligible cost.

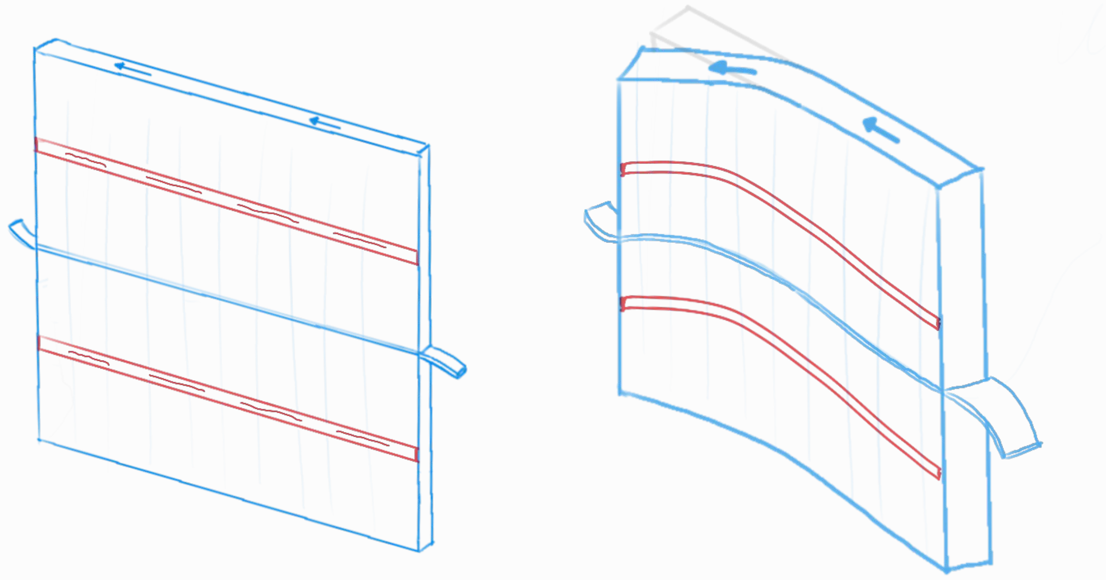


Fig. 123: Backing strip allows for bending, while still imparting compressive resistance

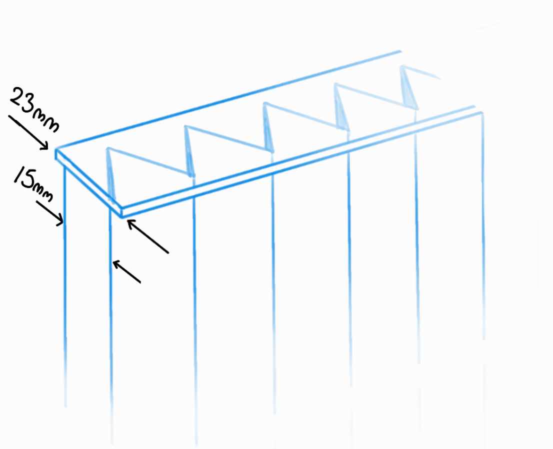


Fig. 124: Difference between filter width and pleat width

10.2.5 No compression

Principle: Filter should not experience compression.

- The primary physical phenomenon that makes it difficult to insert the filter is that the pleats get compressed when pushed in. This deforms the filter and causes it to get stuck. If the system design is modified to ensure the filter does not experience compression, then the filter can be inserted without any issues.

- The rail system is a means of achieving this. In this concept, the compressive force acts on the bracket itself, which is perfectly rigid.
- Users found this idea to be desirable. Its function is easy to intuit, as sliding mechanisms are ubiquitous. It also allows to keep a user's hands free while vacuuming

- Redesign of bracket from the prototyped concept is shown in fig. 125.
  - This new design holds the filter from the back half, leaving the front unobstructed for air to pass through. In case this is not enough to maintain grip on the filter, an alternative design is proposed. As long as the bracket has enough voids in it for air to flow through, it is a feasible design.

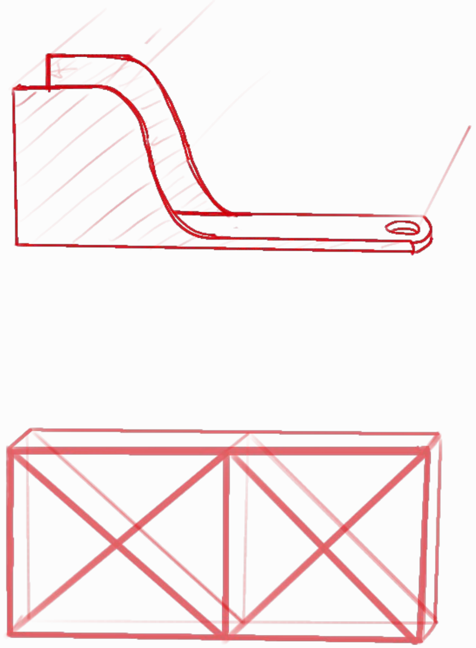


Fig 125: Basic concepts for two kinds of bracket accessory designs. These shapes can be modified to be manufacturable via injection moulding and fit a sliding-rail system.

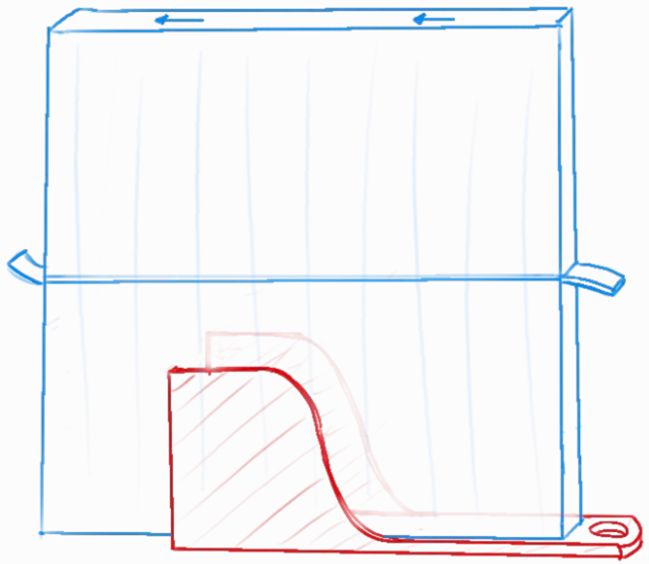


Fig 126: Filter is inserted into drafted bracket from top. This insures a tight fit. Front half of filter with active airflow is unobstructed.

- For the bend in the machine, a possible solution is to leave the filter at an overhang towards the end, which will then bend to take the shape of the slot when the bracket is fully pushed in. This is feasible because:
  - The bracket is drafted, ensuring tight fit of filter when inserted from the top.
  - Only a small area the filter experiences compressive force, while the rest is reinforced. This makes it a lot less likely to bend.
  - The bracket ensures the filter is perfectly centred.
  - Due to the spaceclaim constraints of the skid, the MVHR unit is placed on an extreme end, as close to the wall of the house as possible. This is to ensure the amount of ducting is as little as possible. This means it is not possible to access the filters of this MVHR unit when installed in the front orientation. Hence, it is acceptable that the rails solution for this unit only works in the back orientation.

- The machine already includes guide channels for filters. These could be reused for the rails concept.
  - Using the the in-built guide significantly reduces the complexity of the retrofit. The retrofit would require just a single part i.e. the bracket, which could be sold separately.
  - This bracket could easily slide onto the existing rails, making the retrofit simple enough that the residents may be able to do it by themselves.
  - The bracket can be injection molded. If outsourced, each part would cost 30-40 cents a piece. Using Itho's in-house facilities, the mold would cost 20-30K Euros, but I believe this cost could be lowered further by using less durable molds for lower production quantities.

- Retrofitting in this way would be financially feasible for ITHO for large social housing buildings with hundreds of apartments. [validated claim]. There is already precedence for such a retrofit; Itho has replaced the filter covers for large housing complexes in the past with new covers that are easier to remove.
  - While retrofitting may only be worth the cost to Itho for large complexes, they could still provide the accessories to construction companies. It might be financially viable for them to then conduct the retrofit themselves, saving on future maintenance costs.

- While retrofitting is certainly possible to improve the quality of life of current residents, this principle is a lot easier to implement in a new design.

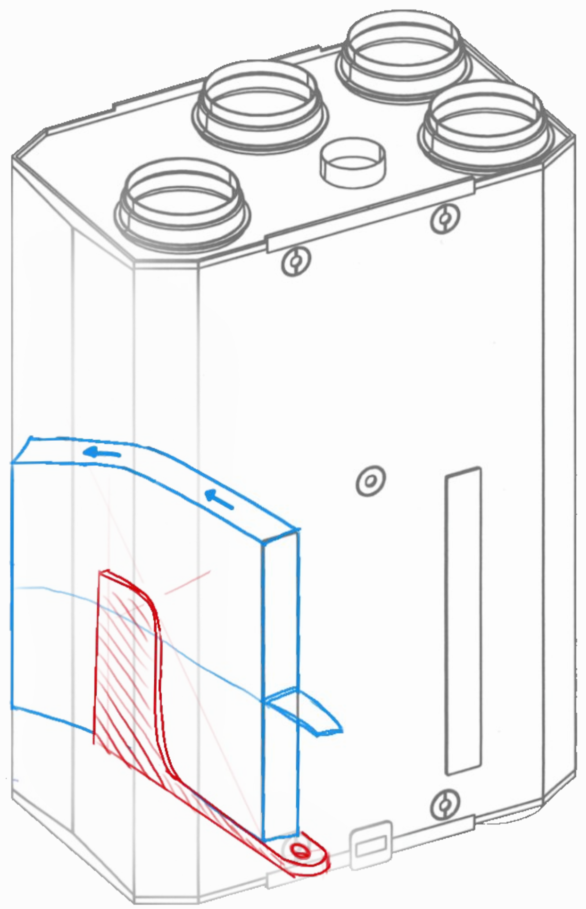


Fig 127: The bracket from the rails concept can be retrofitted to the existing ITHO HRU 300 MVHR unit, even with the bend of the filter slot.

10.2.6 Poka-Yoke

Principle: Filter should only be able to be inserted in a single orientation.

- The Poka-Yoke principle is used in the design of jigs and fixtures in assembly lines. The term comes from Japanese manufacturing and means "error-proofing". This involves designing parts so they can only be assembled in the correct way, without the need for visual confirmation, thus reducing errors. The same principle should be used for filters.

- Residents are unlikely to read manuals or indicators on filters. Similarly, technicians have low incentive to follow instructions. As much as possible, designs should not rely on the user reading instructions.

- A suggestion for an asymmetric filter design is shown in the figure. The top strip of the filter is replaced with a triangular loop, which adds a single operation and minimal cost. This creates a kind of a wedge structure on top of the filter, which slots into a groove into the machine. When attempting to insert the filter in the wrong orientation, it does not fit, guaranteeing the filter will always be in the correct orientation.
  - In case of a retrofit, this groove can be easily incorporated into the bracket design shown previously.
  - For a new design, the slot can be incorporated into the machine itself.

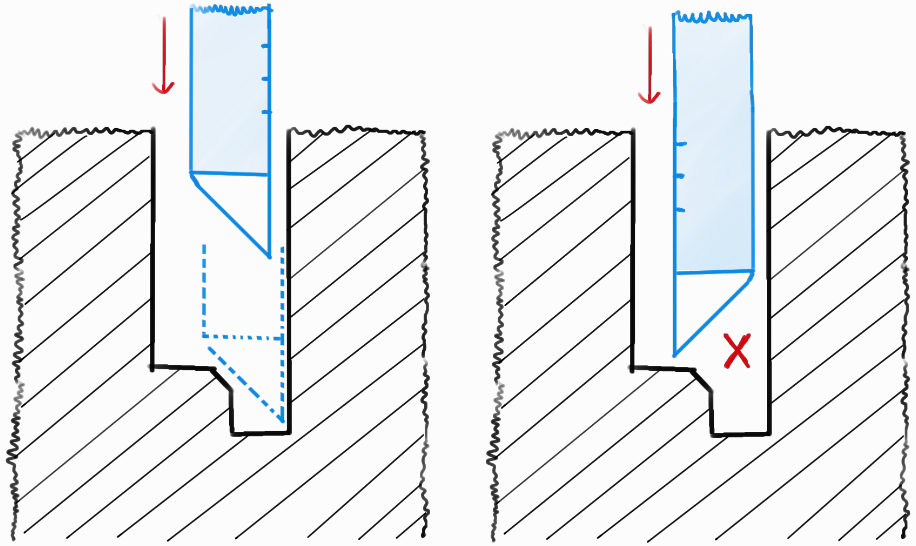


Fig 128: Side view of asymmetrical filter-slot design shows how filter can enter the machine in only a single orientation.

10.2.7 Error Signalling

Principle: Indication for filter cleaning or replacement should be obvious and accurate.

- Error signalling is design principle where errors trigger an obvious indication, such as an alarm, light, or other signal, ensuring the mistake is noticed quickly. This principle is seen in LPG cooking cylinders, where an artificial odour is added to the otherwise odourless gas. This helps immediately detect a gas leak.

- This same principle could be used for the filter clean or replacement indicator. In this machine, the error codes activate on a timer, which is not indicative of the cleanliness or lack thereof of the filter.
  - An alternative measurement could be used to give a more accurate measurement of filter cleanliness such as fan strain, power draw, volume of air filtered, etc.
  - Most ITHO heatpumps connect to the cloud to transmit data for servicing. This could be leveraged for the MVHR unit if they are in the same skid.
  - Power draw to the individual unit could be measured at the start of filter change as a baseline, and at filter change as the limit. An alert could then be set to replace filters.

10.2.8 Double filters

Principle: Avoid areas with no active airflow in filters.

- Based on stakeholder research and interviews conducted, I believe the biggest health issue to residents from unclean filters to be mold growth.
  - When the filter is rotated and the clean part is exposed to airflow, the dirty half of the filter still remains in the machine. I believe this is even more susceptible to mold growth as air is not flowing through it anymore.
  - If mold grows on the inactive part of the filter, the entire filter is contaminated and must be replaced.

- Thus, I do not think the double filter design actually doubles filter life. Future iterations should use a single-filter with an internal design that allows the filter to be used for at least a year.

10.2.9 Machine slot

Principle: Avoid sharp bends in filter slot

- The sharp bend in the ITHO HRU 300 filter slot makes filter insertion difficult
  - Future iterations should attempt to have a straight slot, or if necessary a gentle curve.

- If this should cause the machine to be less compact, I still believe it would be worthwhile to increase the size as long as the filter slot remains straight.

10.2.10 Filter covers

Principle: Coverings should be able to be safefly removed with minimal force.

- The current filter covers are difficult to remove.
- Future iterations should have covers that can be removed with a single hand.
- If possible, the covers should stay attached to the machine so that the user does not have to hold on to them while changing the filters.

11. Conclusion

This chapter presents the conclusions of the thesis, addressing the key findings and insights gained throughout the research. It also discusses the limitations encountered during the study, offers recommendations for future work, and includes my personal reflection on the project and its outcomes.

11.1 | Conclusions

The primary research problem addressed in this thesis is to find ways to improve the quality of life for users by making their interactions with energy-efficient systems more user-friendly.

This research proposes ten principle solutions aimed at Original Equipment Manufacturers (OEMs) of Mechanical Ventilation with Heat Recovery (MVHR) systems. These solutions are feasible and directly target the root causes of the disparity between residents and the systems they use.

The report expands on existing knowledge about energy-efficient housing renovations by combining technical and user-centered perspectives. Skid-type renovations were used as a reference point to narrow the scope, and understanding the domain and the perspectives of stakeholders led to the focus on rented social housing apartments.

This was identified as an area where residents would benefit most from the renovation of skid-type systems. A key conclusion from the research is that many interactions with energy-efficient ventilation systems, especially those implemented as part of a skid, cause significant physical and cognitive strain and can be redesigned to reduce these issues.

Access to the housing complex in Vlaardingen allowed the use of the skid and the equipment there as reference points for redesigns. This focus on retrofitting solutions helped to make the proposals grounded in practical reality.

Prototypes were developed and extensively tested with the same two residents interviewed in previous stages of the research. They found many aspects of the rail systems useful, and certain aspects of the filter modifications were considered interesting, offering ideas for further improvements.

Discussions with various stakeholders provided additional insights, leading to further modifications to the designs and the distillation of information into ten principles for the design of MVHR systems. These principles consider not just the residents as end-users, but also the maintenance and installation technicians.

The principles were validated by an engineer from ITHO, with most being implemented in the company's new machine design set to be released early next year. A few principles were recognized as valuable ideas that had previously been overlooked, and many of the retrofitting solutions were found to be feasible and viable.

In conclusion, the proposed solutions are practical suggestions that have the potential to significantly improve the quality of life for residents in energy-efficient housing.

11.2 | Limitations

The project is proposed within the context of skid-based energy-efficient systems, focusing on improving user interactions with these systems. While ventilation was the primary focus, skid construction emerged as a close second in the solution space. This area has significant potential for further exploration and could serve as the foundation for a completely new project.

As an independently conducted project, the validation of many technical details was only possible through brief interviews with an equipment manufacturer during the final stages. Although this did not majorly impact the project's outcomes, there are areas where implementation could be improved with access to company resources, such as confidential technical files and deeper collaboration with industry experts.

Field access and equipment inspection were limited to just two visits throughout the project. This restricted access required me to rely on alternative methods to gather information, which may have affected the depth of insights gained from direct observations and testing.

The prototype developed during the project was modeled after a specific ITHO machine. As a result, some of the proposed solutions may address issues unique to that particular model. To make the manufacturer advice more universally applicable, other models should be analyzed to ensure that the solutions are not limited to ITHO machines alone.

Additionally, the prototype was low fidelity, and some manufacturing constraints became apparent during user testing. These limitations influenced user opinions, and while efforts were made to account for these factors in the analysis, they may have affected the overall findings.

Lastly, as someone new to the domain of energy-efficient housing, I approached the problem from a fresh perspective. However, this also meant that I had a limited understanding of standard industry practices, and in some cases, I may have inadvertently reinvented existing solutions.

11.3 | Future Recommendations

To enhance this project further, I recommend the following steps:

First, interview other influential stakeholders. I had been working on setting up an interview with a policymaker from the European Union, but due to time constraints, this was not possible. This interview would provide valuable insights from the government’s perspective, offering another angle on the requirements that need to be addressed.

Next, collaborate with a manufacturer, ideally ITHO, to thoroughly evaluate the potential of the proposed principle solutions. This collaboration could assess the viability of these solutions, identify any ideas that were previously overlooked, and explore whether certain solutions raise interesting points that need further validation.

For ITHO specifically, the next step would be to conduct a cost-benefit analysis of implementing these solutions as retrofits. This analysis should consider the impact not just on the manufacturer, but also on other stakeholders. For instance, ITHO could take on the cost of designing and manufacturing the accessory, while the social housing company could handle installation costs, leading to future savings on maintenance.

Once a decision has been made on whether to pursue retrofitting with ITHO or explore new solutions for MVHR manufacturers in general, the next step would be to remake the prototypes. These improved prototypes would then be subjected to more user testing, with a focus on specific aspects that require further exploration.

In parallel, the technical feasibility of implementing the most promising solutions should be researched to ensure that they are practical and effective in real-world applications.

11.4 | Personal Reflections

The initial phase of this project was the most challenging and time-consuming. It took me considerable time to understand the context of housing in the Netherlands, the systems involved, and the key stakeholders.

Initially, I was hesitant about spending so much time on setup, but this decision ultimately proved to be beneficial. It was critical to make informed choices early on, as getting locked into an arbitrary decision could have negatively impacted the project's direction.

Once I had made a solid choice, I was able to move forward at a much quicker pace. In future projects, I would focus on communicating more clearly about the specific aspects of a problem that need to be understood before making such important decisions. Tackling a problem of this wide a scope was an interesting experience for me, since I am usually used to having more constraints to begin with.

Navigating this thesis involved dealing with many unknowns. The design process was highly non-linear due to the diversity of systems, numerous possible design directions, and the difficulty in obtaining reliable technical information.

Much of my time was spent finding information through various sources, including technical guides, ISO standards, manuals, and commercial websites. Sometimes, I had to be creative such as making deductions from the absence of information in technical manuals. As time progressed, I learned to trust my own instincts as a design engineer so be able to make confident claims from multiple, often conflicting sources of information,

One of my primary learning goals for the project was to improve my prototyping skills, especially with methods other than 3D printing. Since much of the concept development took place towards the end of the project, along with prototyping, I learnt how to plan my processes, adapting quickly to changing situations, and to make the most out of opportunities that cropped up.

User testing provided valuable insights, especially through the interviews I conducted. Having Stella accompany me during the interviews allowed me to get immediate feedback, which helped me adjust my interviewing techniques to gather more valuable information.

At the start of the project, I was unsure how to proceed with the limited information at hand. However with time, I learned to take more initiative and be more resourceful, choosing my own direction and getting support from my supervisory team.

The most hard-learned lesson was the significance of documentation. I have a tendency to prioritize achieving results over documenting my findings. As a result, I had to spend considerably more time and effort than I had expected in converting my personal shorthand notes into a format that could be communicated to a broader audience. In future projects, I plan to start documenting earlier and invest in learning software that is better suited for design reports.

Overall, despite a few speed bumps along the way, I thoroughly enjoyed this project and feel that it has made me a better designer. I am satisfied with the end result and hope that it provides useful insights that can genuinely improve the quality of life for users.

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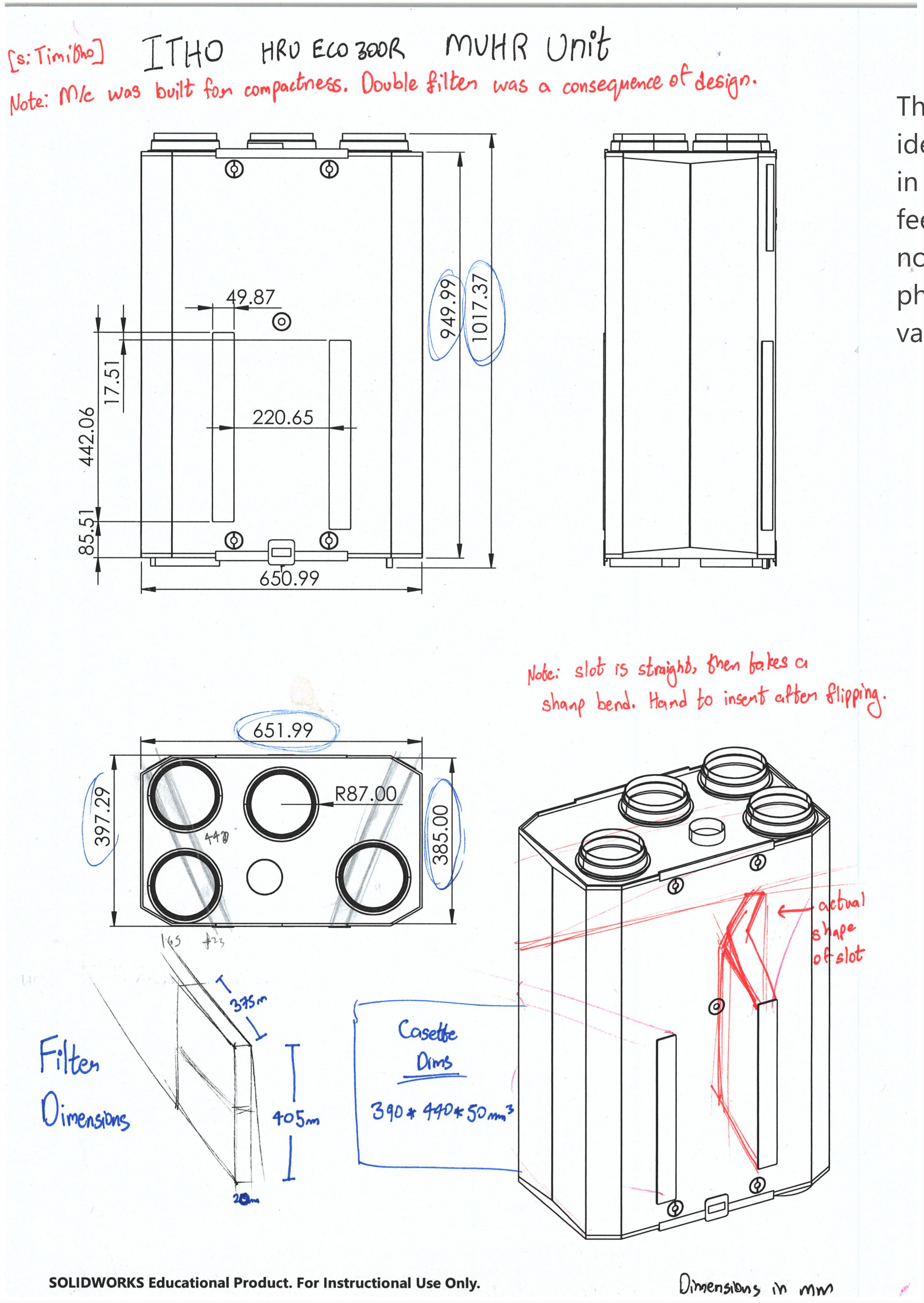
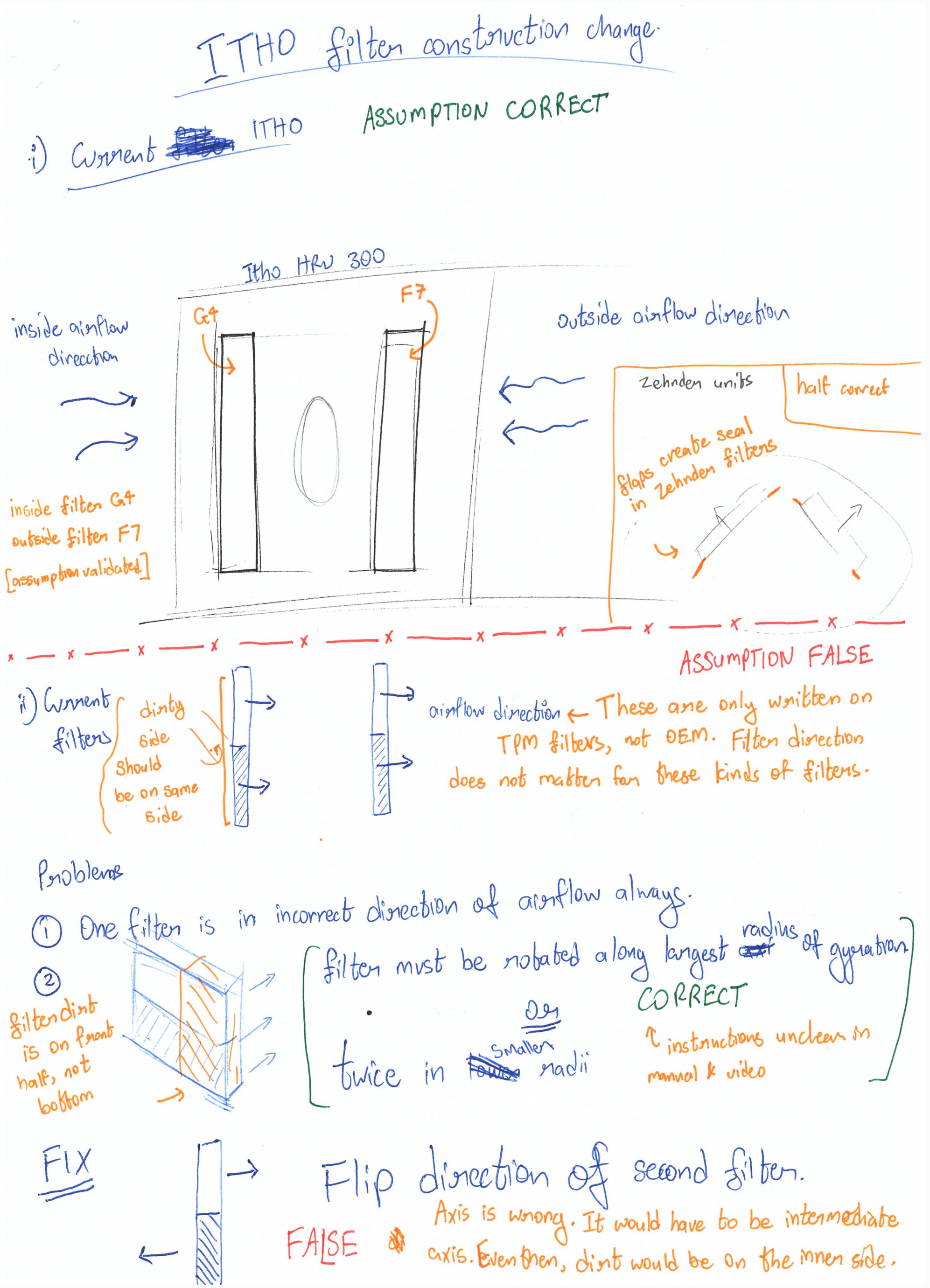


This section shows most of the ideation I had come up with. Notes in red and orange are personal feedback on those previous ideas, noted at the end of the evaluation phase to see which ideas were validated and which ideas were not.



Filter modifications

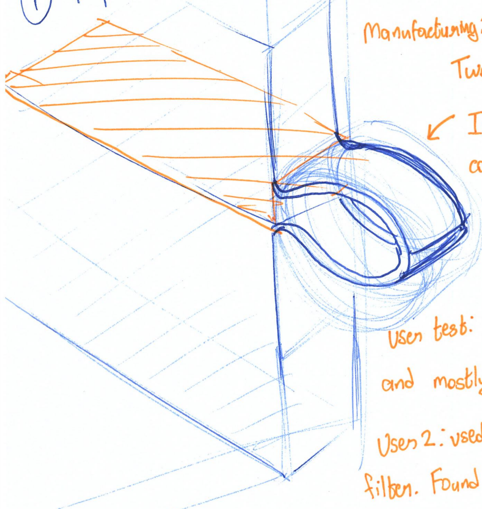
CORRECT

①

① Pulling

(i) Replace pull tab with loop

- loop can be hooked
- finger on mechanism



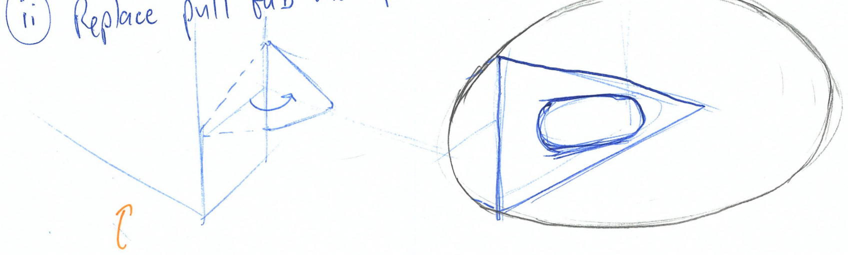
Manufacturing: Two filters and filter tab is manually glued [Ifno]

It is possible to replace with loop if added cost is not too much [should not be too much]

User test: User 1 did not use ~~pull tab~~ loop at all in most cases and mostly yanked on filter. Even when used, used like pull tab. User 2: used tab and loop to pull out a little bit, then grabbed filter. Found loop a bit more useful due to long nails.

- same principle, less sturdy, easier to manufacture

(ii) Replace pull tab with punched tab



Design could be possible for Zehnder filters, but still unknown.

May be too fragile and reduce surface area for gripping. perhaps unnecessary. Especially if filter width is reduced for easier entry

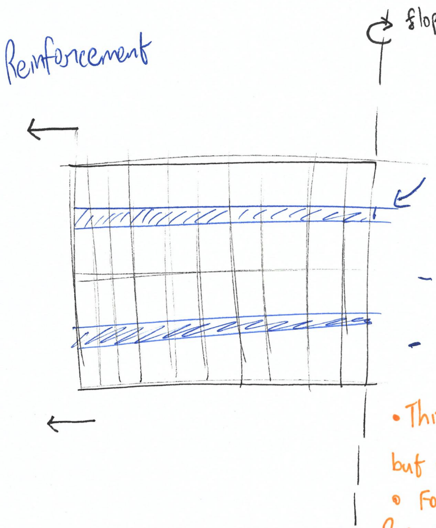
② Floppiness

Filter modifications

②

(i) Reinforcement

PLAUSIBLE



filter reinforced by thin strips

- V1 prototype could be cardboard
- reinforcement on filter back

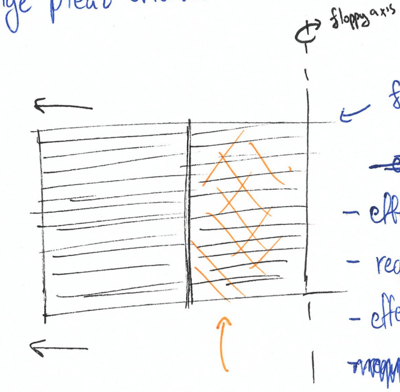
• This kind of reinforcement allows for bending but otherwise stiffens filter

• Found in Zehnder filters.

? is it an added manufacturing process?

(ii) Change pleat orientation

SEMI PLAUSIBLE

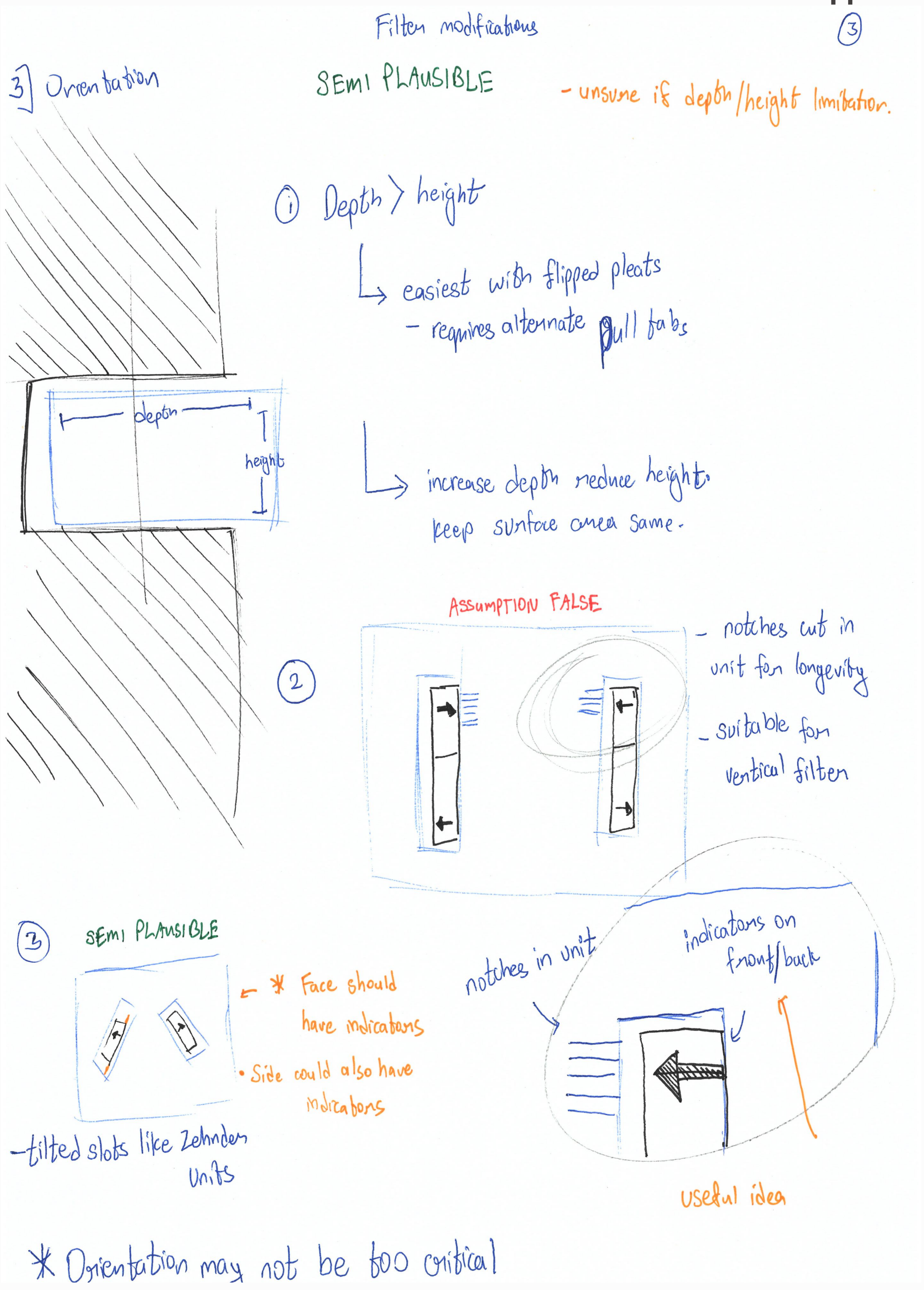


flip pleat orientation

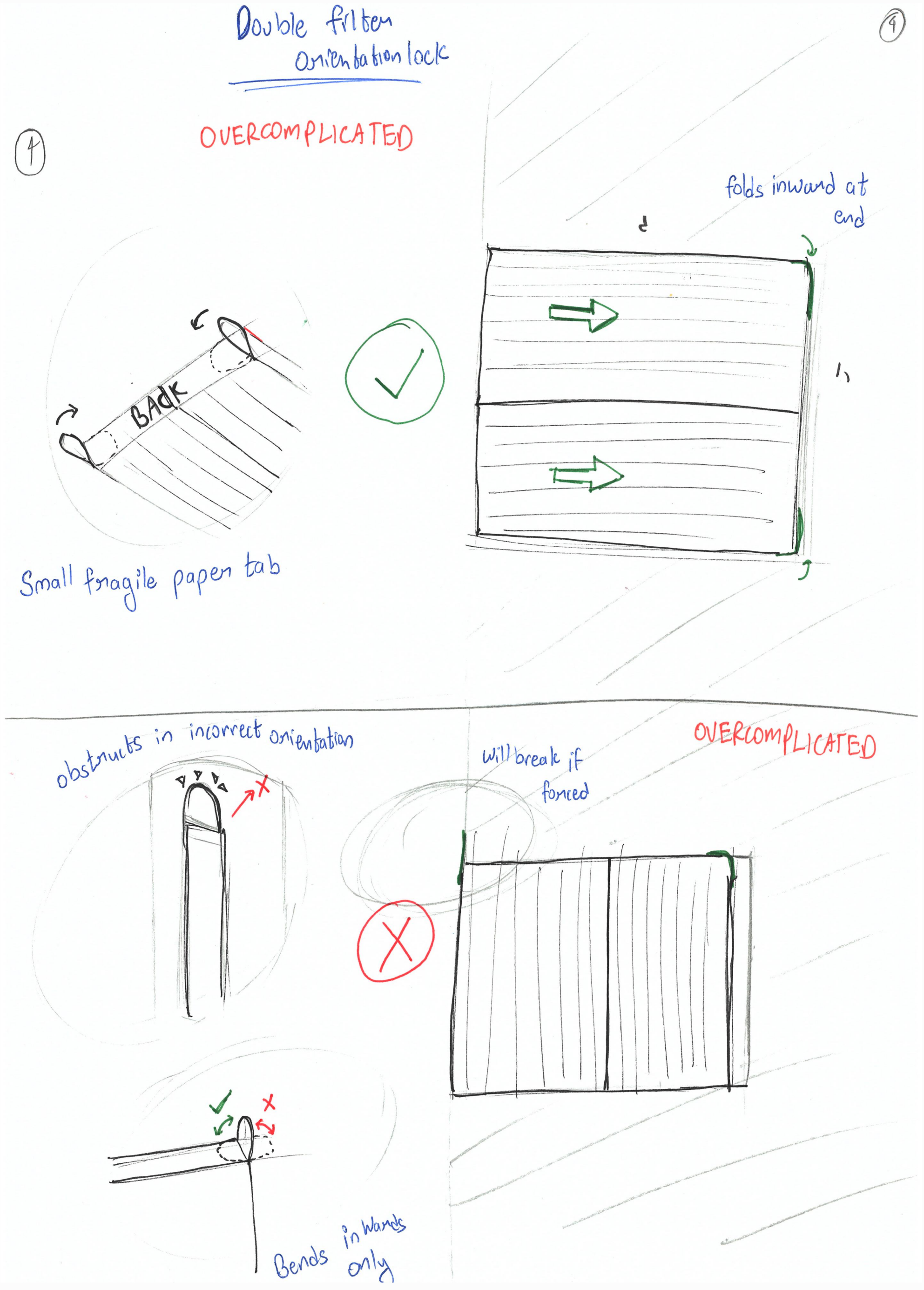
- effect on filter durability unknown
- requires filter dimension change
- effect on filter effectivity unlikely.

+ since airflow is front half, will make the filter a lot more intuitive

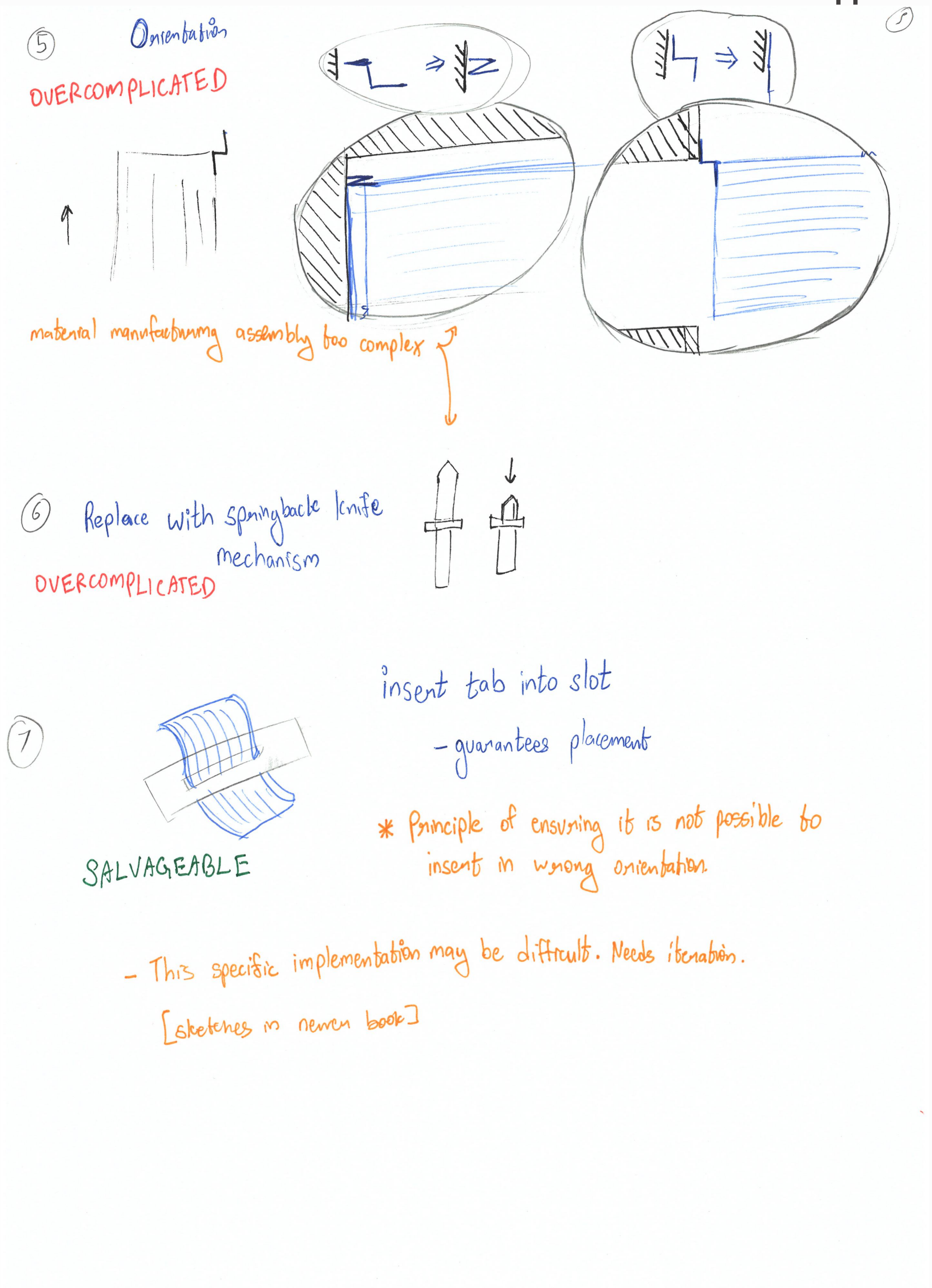
- in this orientation, pleats do not bend.

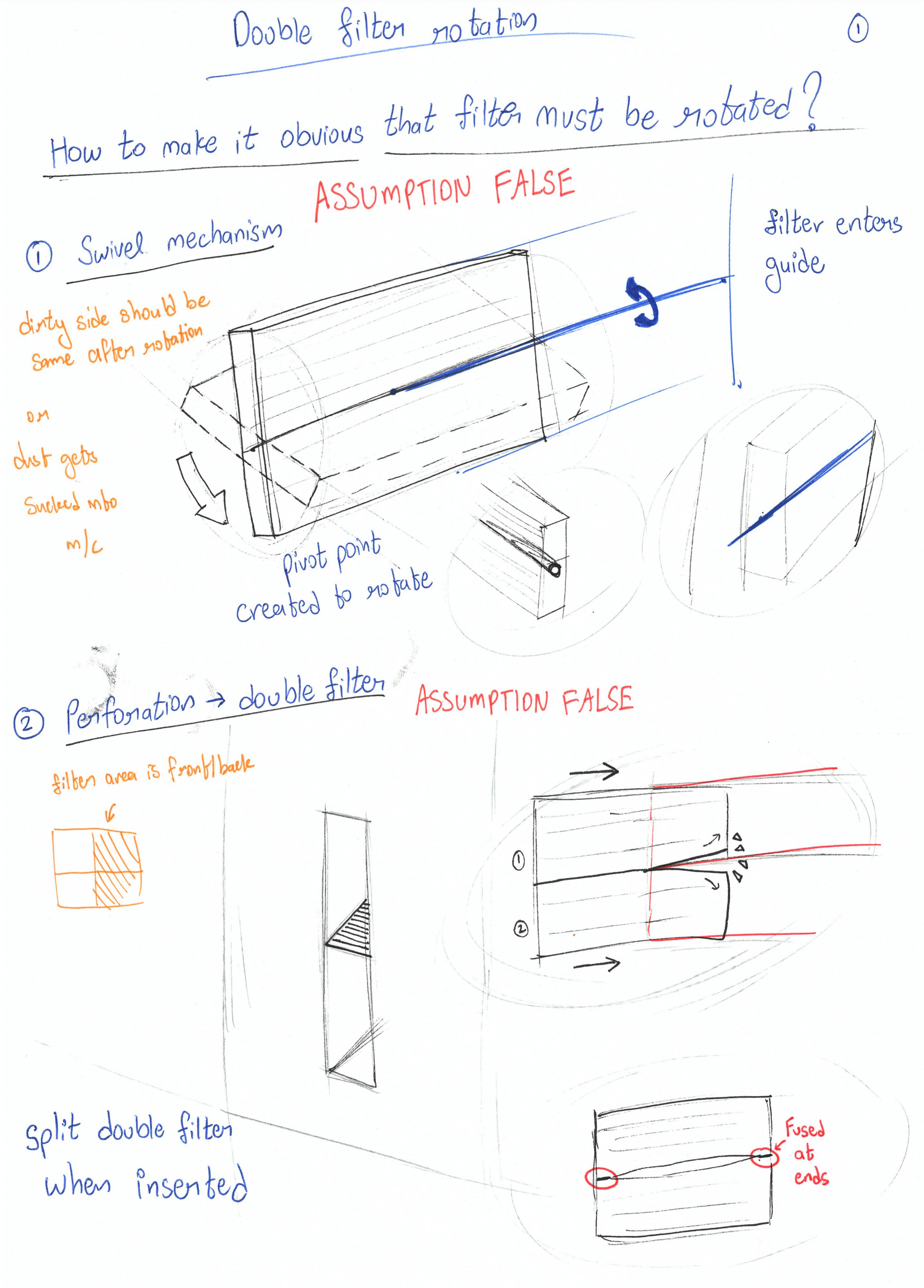


Filter modifications
3
3] Orientation
SEMI PLAUSIBLE
- unsure if depth/height limitation.
① Depth > height
easiest with flipped pleats
- requires alternate pull tabs
depth
height
increase depth reduce height.
keep surface area same.
ASSUMPTION FALSE
② - notches cut in unit for longevity
- suitable for vertical filter
③ SEMI PLAUSIBLE
* Face should have indications
• Side could also have indications
- tilted slots like Zehnder units
notches in unit
indications on front/back
useful idea
* Orientation may not be too critical

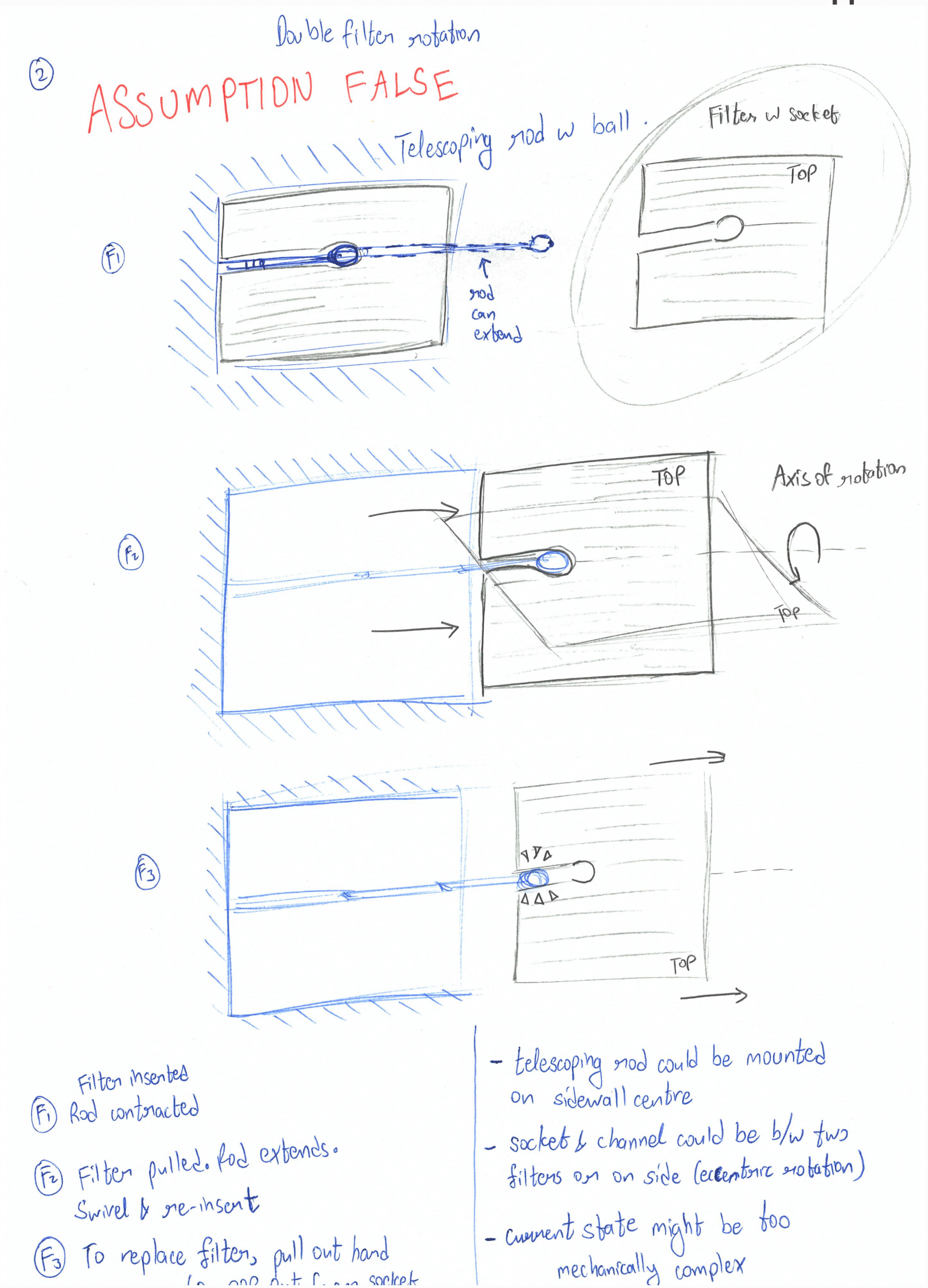


Double filter
Orientation lock
4
①
OVERCOMPLICATED
folds inward at end
BACK
Small fragile paper tab
obstructs in incorrect orientation
will break if forced
OVERCOMPLICATED
Bends inwards only

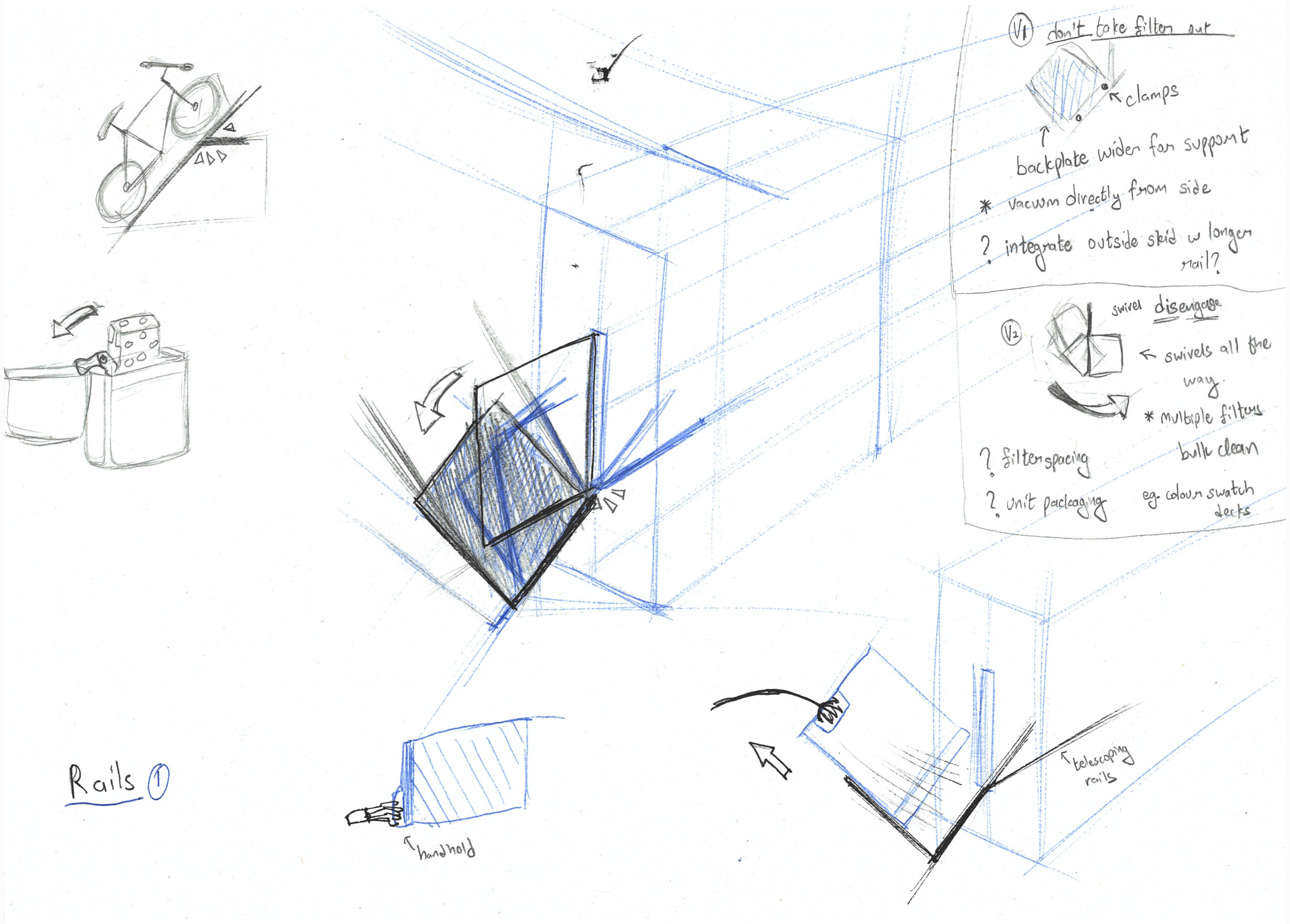

(5) Orientation
OVERCOMPLICATED
material manufacturing assembly too complex
(6) Replace with springback knife mechanism
OVERCOMPLICATED
(7)
SALVAGEABLE
insert tab into slot
- guarantees placement
* Principle of ensuring it is not possible to insert in wrong orientation
- This specific implementation may be difficult. Needs iteration.
[sketches in newer book]


Double filter rotation
(1)
How to make it obvious that filter must be rotated?
ASSUMPTION FALSE
(1) Swivel mechanism
filter enters guide
dirty side should be same after rotation
or
dust gets sucked into m/c
pivot point created to rotate
(2) Perforation → double filter
ASSUMPTION FALSE
filter area is front/back
Split double filter when inserted
Fused at ends

Appendix A: Ideation (Evaluated)



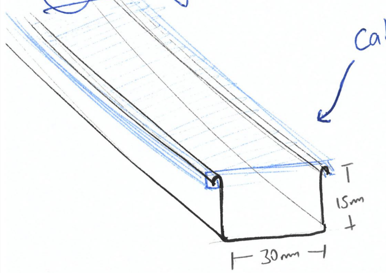
Appendix A: Ideation (Evaluated)



2

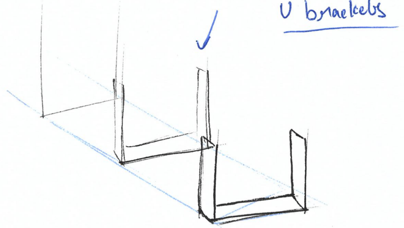
I Rails — PLAUSIBLE

V1 Prototype



cable ducting scrap

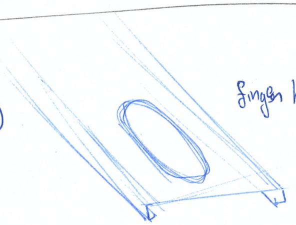
bolt series of U brackets



• Use plastic duct as rails

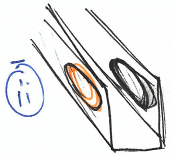
V2 & other future considerations

i

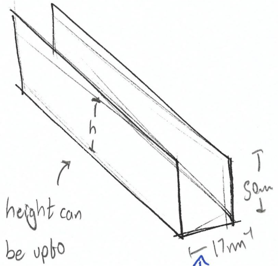


finger hole for grip

ii



grooves in sides of rails might be better.



height can be upto half of filter

User testing

- Works smoothly. Preferred by both users, though User 1 stated they might not need it.
- hand grooves were not used.
- first instinct always to pull on filter
  ↳ maybe if channel was drafted, filter locks in better.

? what do about curved end?

? what about endstop / stability at full extension

? retrofitting?

long bracket

- lasercut / metal / 3D printed for proto
- final could be injection moulded for flexibility.

✳ can add directionality?

Rails V2

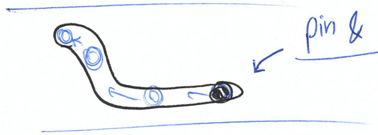
3

Bending?

TOO SPECIFIC

How to add the tilt?

i



pin & slot mechanism

[Similar to old computer keyboards]

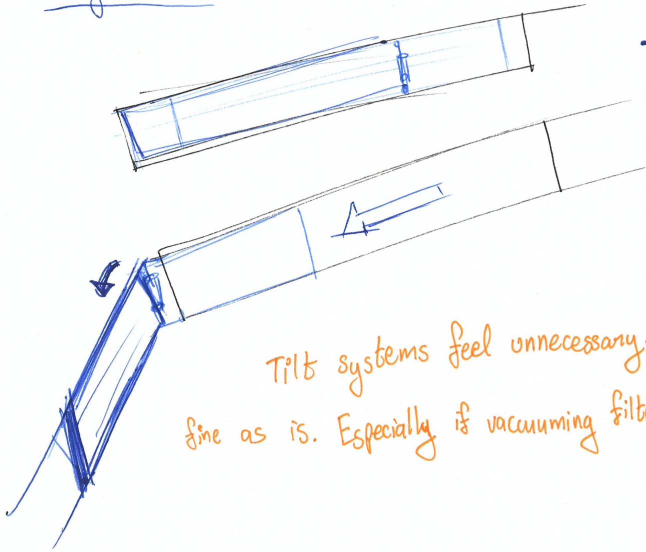
~~ii Filter geometry~~

TOO SPECIFIC

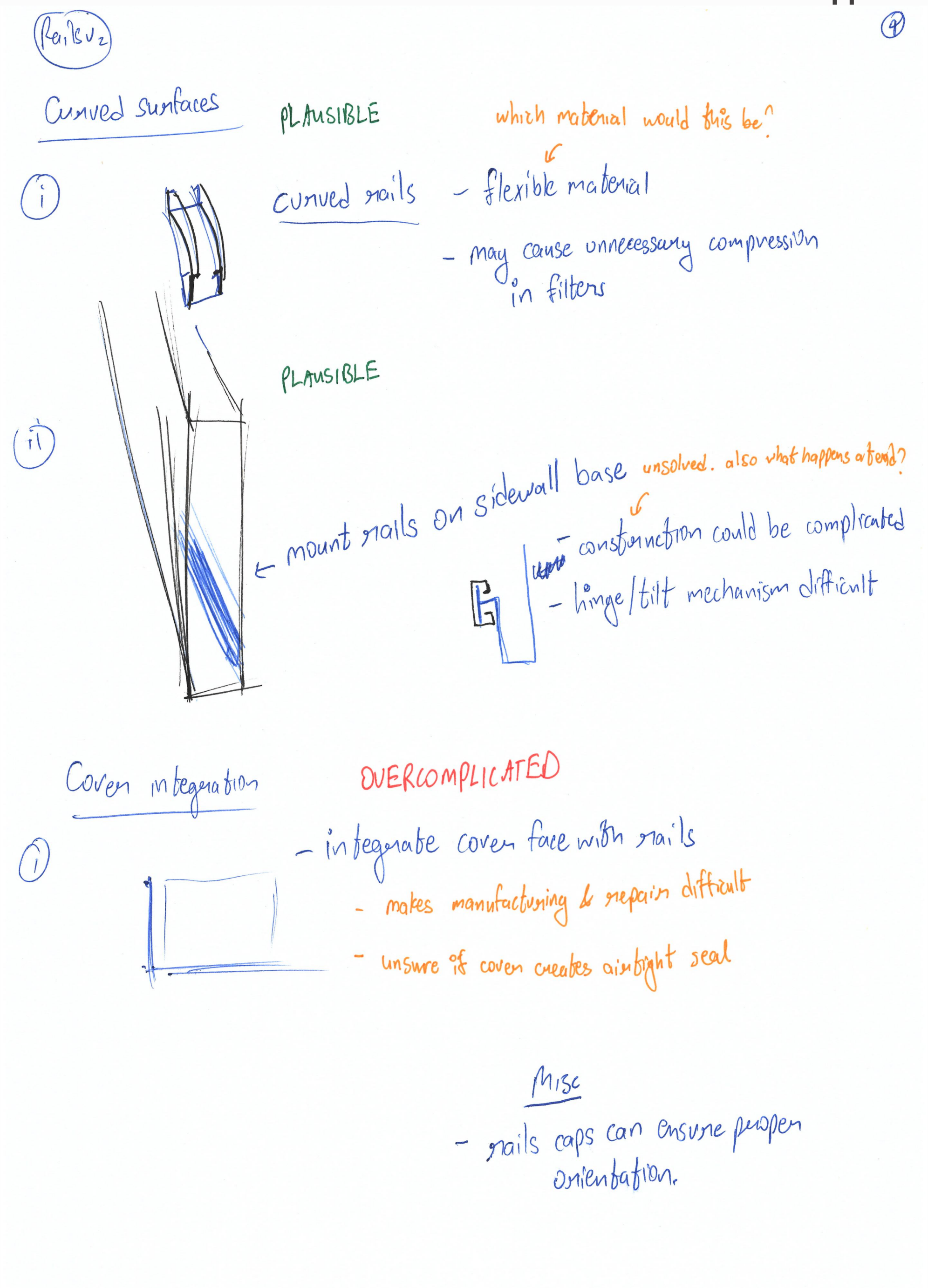
ii Hinged section

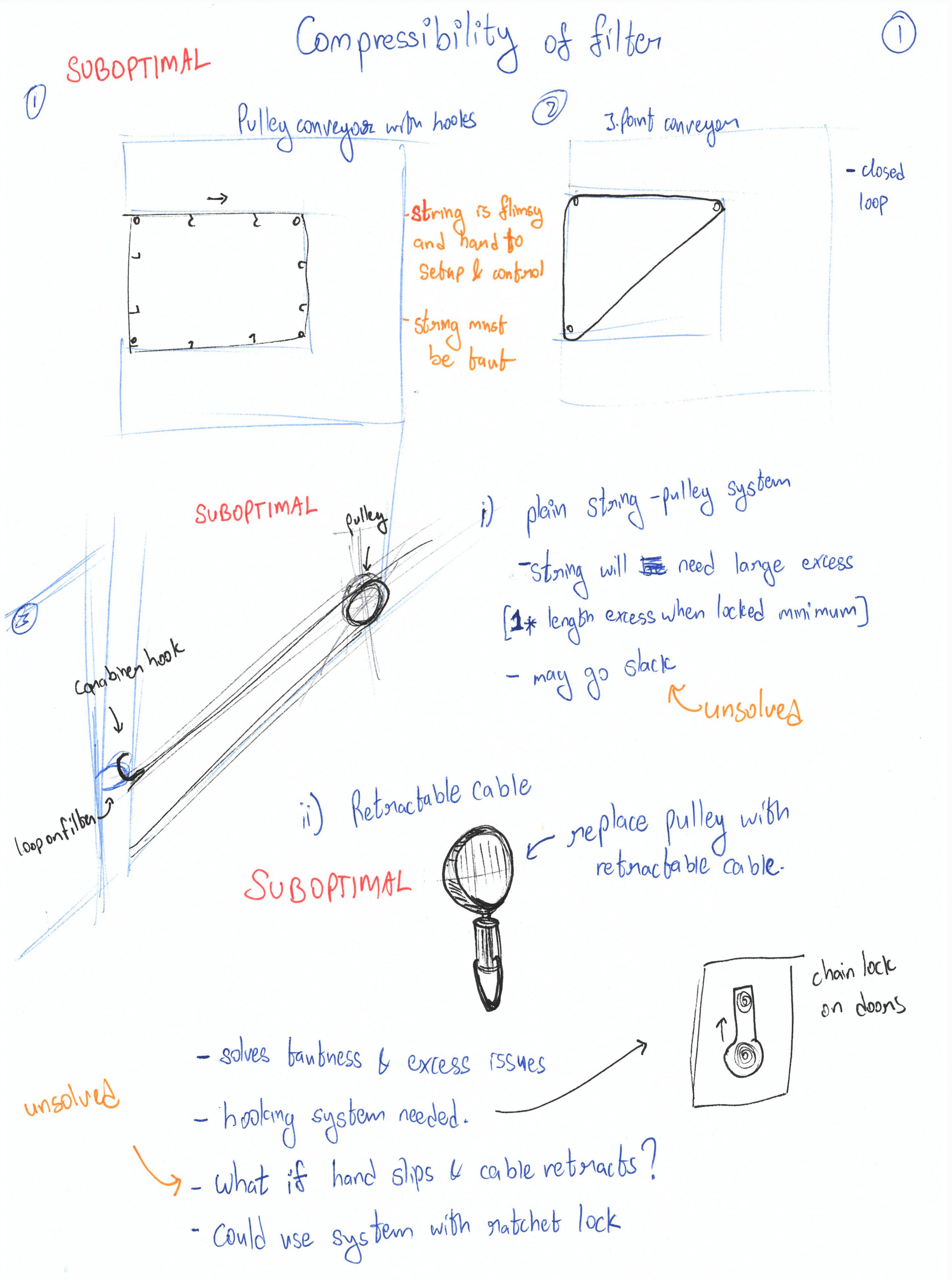
↑ can work

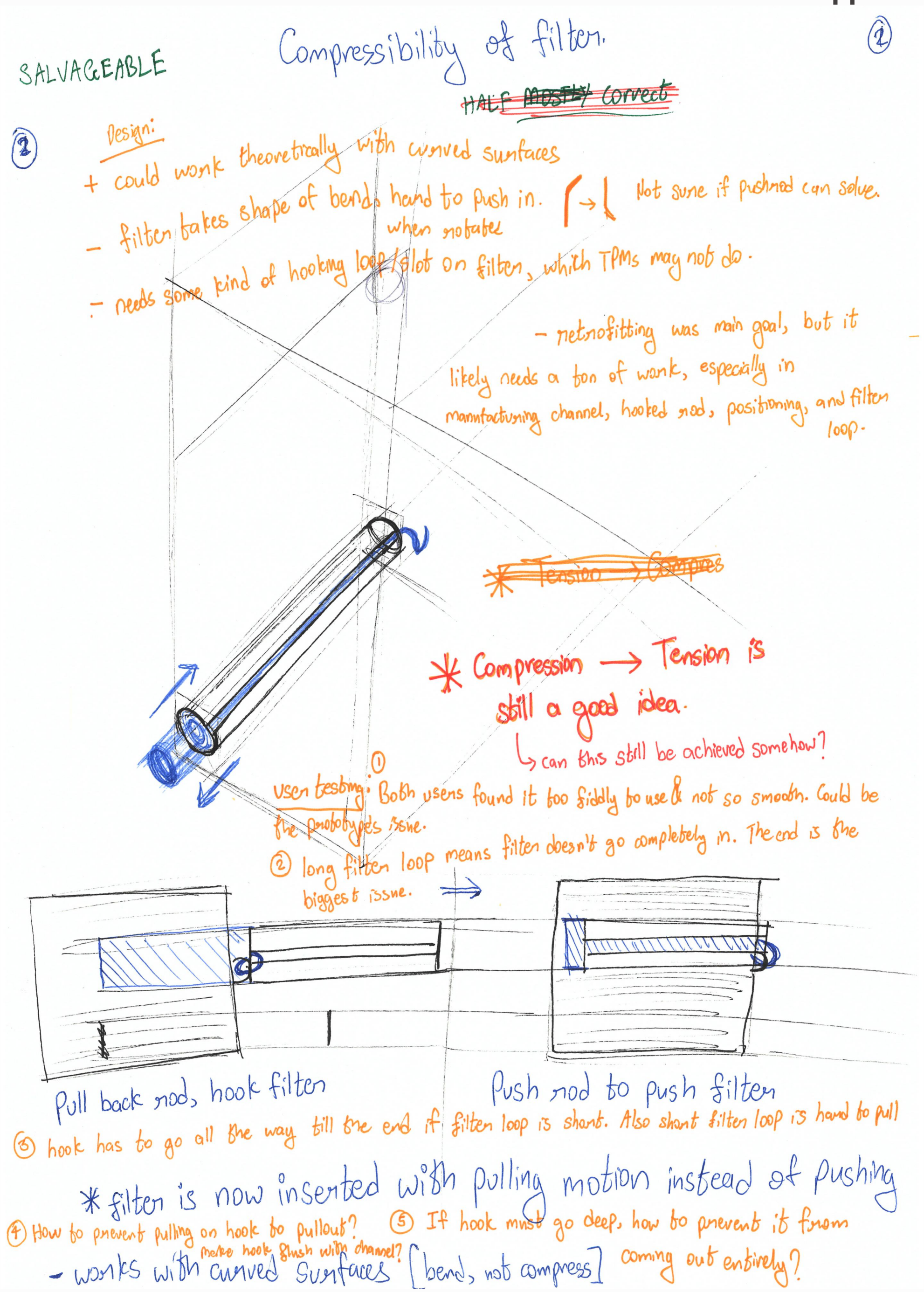
- Steel rail bends inward
- pre-punched for bolting
- may not work for curved surface

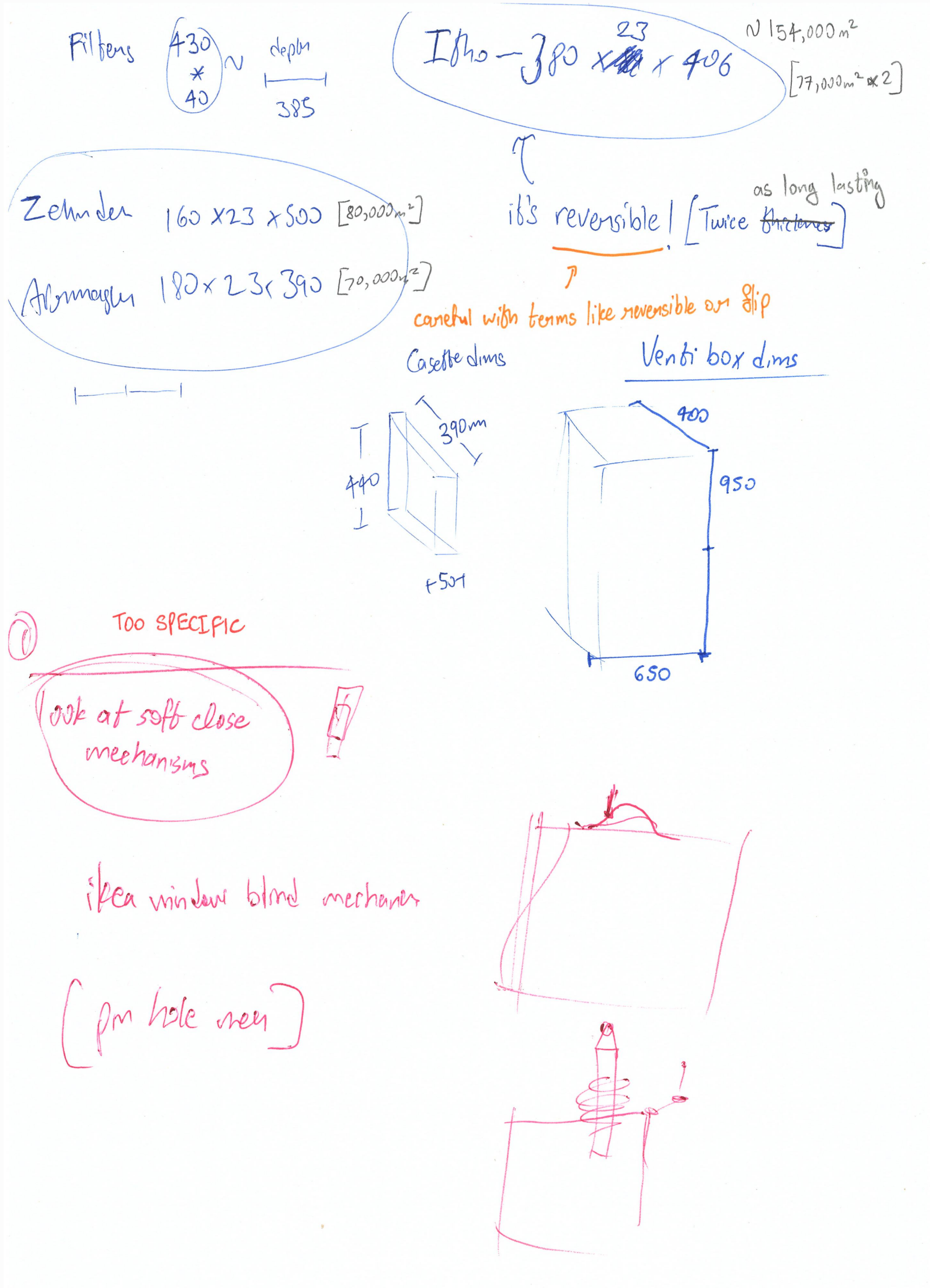


Tilt systems feel unnecessary. Rails work fine as is. Especially if vacuuming filters is a lower priority.


Rails v2
4
Curved surfaces
PLAUSIBLE
which material would this be?
i
curved rails
- flexible material
- may cause unnecessary compression in filters
PLAUSIBLE
ii
unsolved. also what happens at end?
← mount rails on sidewall base
- construction could be complicated
- hinge/tilt mechanism difficult
Cover integration
OVERCOMPLICATED
i
- integrate cover face with rails
- makes manufacturing & repair difficult
- unsure if cover creates airtight seal
Misc
- rails caps can ensure proper orientation.


Compressibility of filter
1
SUBOPTIMAL
1
Pulley conveyor with hooks
2
3-Point conveyor
- closed loop
- string is flimsy and hard to setup & control
- string must be taut
SUBOPTIMAL
pulley
i) plain string-pulley system
- string will need large excess
[1* length excess when locked minimum]
- may go slack
unsolved
carabiner hook
loop on filter
ii) Retractable cable
SUBOPTIMAL
replace pulley with retractable cable.
chain lock on doors
- solves tautness & excess issues
unsolved
- hooking system needed.
- what if hand slips & cable retracts?
- Could use system with ratchet lock


SALVAGEABLE
Compressibility of filter.
HALF MOSTLY correct
Design:
+ could work theoretically with curved surfaces
- filter takes shape of bend, hard to push in. when rotated
Not sure if pushrod can solve.
- needs some kind of hooking loop/slot on filter, which TPMs may not do.
- retrofitting was main goal, but it likely needs a ton of work, especially in manufacturing channel, hooked rod, positioning, and filter loop.
Tension → Compress
* Compression → Tension is still a good idea.
↳ can this still be achieved somehow?
User testing: Both users found it too fiddly to use & not so smooth. Could be the prototypes issue.
② long filter loop means filter doesn't go completely in. The end is the biggest issue.
Pull back rod, hook filter
Push rod to push filter
③ hook has to go all the way till the end if filter loop is short. Also short filter loop is hard to pull
* filter is now inserted with pulling motion instead of pushing
④ How to prevent pulling on hook to pullout? make hook flush with channel?
⑤ If hook must go deep, how to prevent it from coming out entirely?
- works with curved surfaces [bend, not compress]


Filters
430 * 40
depth
385
Itho - 380 x 23 x 406
~154,000 m²
[77,000 m² x 2]
Zehnder 160 x 23 x 500 [80,000 m²]
Airmaster 180 x 23 x 390 [70,000 m²]
it's reversible! [Twice as long lasting]
careful with terms like reversible or slip
Casette dims
Venti box dims
390mm
440
400
950
650
TOO SPECIFIC
look at soft close mechanisms
ikea window blind mechanism

Appendix A: Ideation (Evaluated)

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Filter class too high for MVHR

TABLE 1.2 for AIR FILTERS and EFFICIENCY

CLASSIFICATION	Mean Fractional Efficiency	IEST RP-CC001.3	European Union EN1822 Class		Typical Controlled Contaminant	Application	MAYAIR Range of Products
HEPA Filter (H Class)	≥95% at 0.3µm	n/a	H10	≥85% at MPPS	Particle size bigger than 0.3µm (Virus [unattached]) (Carbon dust) (Sea salt) (All combustion smoke) (Radon progeny)	All types of cleanrooms	M-HI
	≥98% at 0.3µm		H11	≥95% at MPPS			M-HV
	≥99.97% at 0.3µm	TYPE A					M-CFCN
	≥99.99% at 0.3µm	TYPE C	H12	≥99.5% at MPPS			M-CAM
	≥99.995% at 0.3µm		H13	≥99.95% at MPPS			M-TMI
	≥99.999% at 0.3µm	TYPE D	H14	≥99.995% at MPPS			M-FFU
ULPA Filter (U Class)	≥99.9995% at 0.12µm	TYPE F	U15	≥99.9995% at MPPS	Particle size bigger than 0.12µm	super cleanroom	M-HV & M-CAM
	≥99.99995% at 0.12µm		U16	≥99.99995% at MPPS			M-CFCN
	≥99.999995% at 0.12µm		U17	≥99.999995% at MPPS			M-FFU

Note :

1. AFI : American Filter Institute
2. NBS : National Bureau of Standards
3. ASHRAE : American Society of Heating Refrigerating & Air-conditioning Engineers
4. MERV : Minimum Efficiency Reporting Value
5. MPPS : Most Penetrating Particle Size
6. HEPA : High Efficiency Particulate Air Filter
7. ULPA : Ultra Low Penetration Air Filter
8. Am : Average Arrestance Efficiency for Coarse Filters
9. Em : Average Efficiency for Fine Filters
10. IEST : Institute of Environmental Sciences and Technology

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Note: This is an old comparison chart.
It has been succeeded by ISO 16890

TABLE 1.1 for AIR FILTERS and EFFICIENCY

Coarse filter. Inside air or Outside air { (PRE Filter)

Fine filter Outside air. { (F7–F9)

CLASSIFICATION	Arrestance or Dust Spot Efficiency	US ASHRAE 52.2	European Union EN779 Class		Typical Controlled Contaminant	Application	MAYAIR Range of Products
PRE Filter (G Class)	AFI <65 %	MERV 1	G1	Am< 65%	Particle bigger than 10.0µm (Pollen) (Spanish moss) (Dust mites) (Sanding dust) (Spray paint dust) (Textile fibers)	Gross filter, domestic and commercial	M-NET
	AFI 65%-70%	MERV 2	G2	65%≦Am< 80%			M-WASH
	AFI 70%-75%	MERV 3					ROLL MEDIA
	AFI 75%-80%	MERV 4					
	AFI 80%-85%	MERV 5	G3	80%≦Am<90%	Particle size within 3.0µm-10.0µm (Mold) (Spores) (Hair spray) (Cement dust) (Snuff) (Powdered milk)	Commercial, industrial, paint shop	M-NET
	AFI 85%-90%	MERV 6					M-WASH
	NBS 25%-30%	MERV 7	G4	90%≦Am			M-DP
	NBS 30%-35%	MERV 8					ROLL MEDIA
MEDIUM Filter (F Class)	NBS 40%-45%	MERV 9	F5	40%≦Em< 60%	Particle Size within 1.0µm-3.0µm (Lead dust) (Milled flour) (Coal dust) (Auto emissions) (Nebulizer drop) (Welding fumes)	IAQ concerned commercial & industrial, medical	M-PACK
	NBS 50%-55%	MERV 10					M-BOX
	NBS 60%-65%	MERV 11	F6	60%≦Em< 80%			M-MI, M-MII
	NBS 70%-75%	MERV 12					M-MV
	NBS 80%-85%	MERV 13	F7	80%≦Em< 90%	Particle size within 0.3µm-1.0µm (All bacteria) (cooking oil) (Most smoke) (Copier toner) (Most face powder) (Most paint pigments)	IAQ concerned commercial, industrial, medical, food etc	M-PACK
	NBS 90%-95%	MERV 14	F8	90%≦Em< 95%			M-BOX
	NBS>95%	MERV 15	F9	95%≦Em			M-MI, M-MII
		MERV 16					M-MV

Skid Frame

A 1:1 scale skid frame was built to get an understanding of location, positioning, access points of components. The dimensions of the skid were obtained from the drawing sheets of the Vlaardingen apartments.

The frame is built with wooden beams and screws. I made use of an existing scrap structure lying around the workshop, and extended one of the sides by half a metre to build the final frame. This was a large time saver as opposed to building the structure from scratch.

The final dimensions are reasonably close to those of in the drawing file.

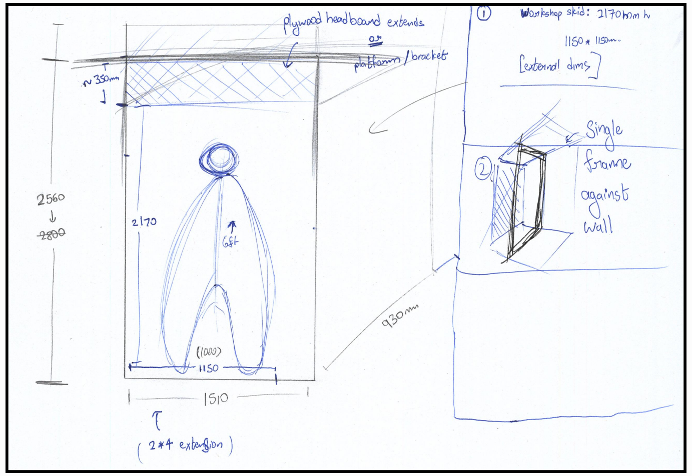

Fig X: Skid Calculations

Fig X: Original scrap structure

Fig X: Building the skid frame

Fig X: Dismantling and extending frame

Fig X: Final Skid frame

Geometry and Dimensions

Itho filters have greater resistance to tilting as opposed to bending. This is due to the orientation of the pleats. For regular single filters, it would be difficult to manufacture the pleats in the horizontal orientation. However, since double filters are simply two filters glued together, this could be easily achieved.

The vertical or horizontal orientation of pleats does not generally affect the performance of the filter, as long as the correct airflow direction is maintained. [citation needed]. Changing the orientation of pleats would essentially change the axes of the filter, thus improving both bending and compressive resistance, at the cost of tilt resistance.

This is still a net improvement in the stability of the filter. The filter could be further stiffened with the addition of a reinforcing strip at the sides.

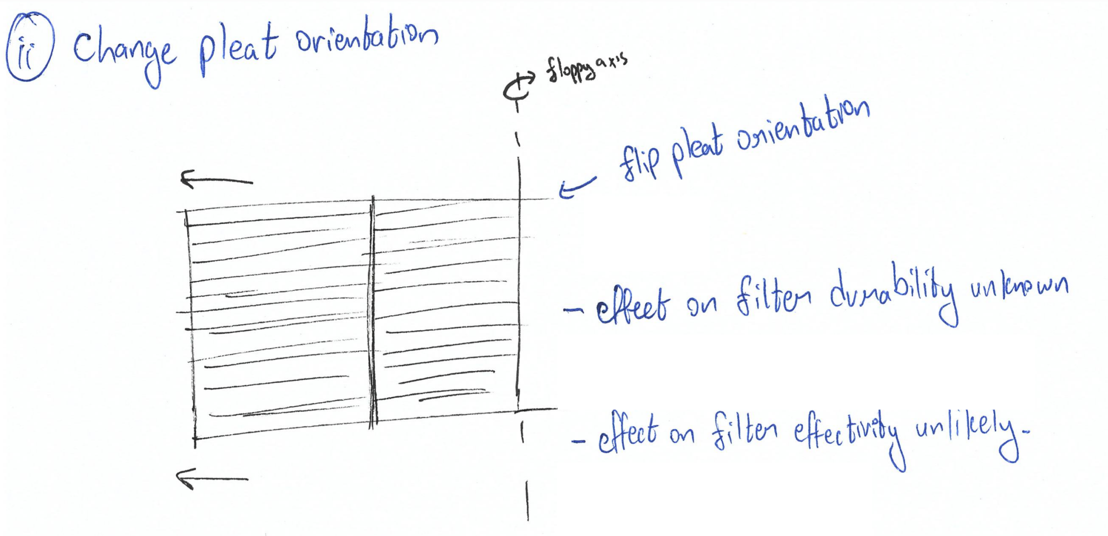

Fig 1: [placeholder] pleat orientation concept sketch

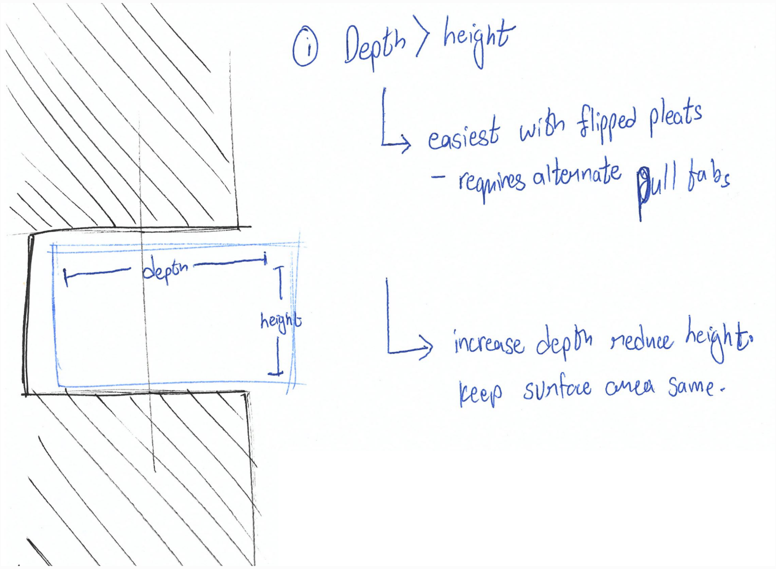

Fig 2: [placeholder] Filter dimensions concept sketch

Alternatively, since the depth and height of double filters is comparable to one another, filters could be designed such that the depth is greater than the height. [Fig 2] This ensures that the filter cannot be inserted on the incorrect axis.

While this is a filter modification, it still requires the OEM to design a compatible MVHR unit first. It also does not prevent insertion in the wrong airflow direction.

[add filter width]

Tim interview 1 notes

- g4 f7 filters inside/outside assumption was validated. However, this instruction is not found in the manual, and is difficult to fully understand.
  - Additionally, OEM and TPM Zehnder filters are colour coded. Itho are not.
- Filter direction assumption fully wrong. Zehnder filters have directions for completely different reasons. Itho filters are bidirectional.
  - TPM filters have airflow direction marked on them. this is incorrect. Doesn't really affect anything, but leads to two sets of conflicting instructions.
- Details of manufacturing process. Roll-bend-glue. Manual job to assemble double filter, including the top/bottom parts.
- Pleat could be 90 degree rotated. It would be more sensible and intuitive for dust pattern as well. But it doesn't bend well in that direction.
- Machine is reversible (front/back) so it is easy to unscrew half and take it out
  - For skids I speculate it would always be installed in backwards position. Because MVHR will always be hugging wall of skid, on left or right (ducting reasons)
- Double filter was a consequence of the machine requirement to be as compact as possible.
  - Regardless, still useful. Since the this Itho MVHR machine is built for compactness, it is likely going to be a popular choice for skids with space constraints.
  - Residents may prefer double filter, as pricepoints are not too high, and with a 6-month filter change recommendation, buying a double filter can be an annual task.

Since filters are bidirectional, direction of entry does not matter. Just that when it is rotated, dirty side should be on the outside. This assumption was validated.

- It takes time for particulate buildup in filter to cause dirty air to pass through, since the small particles stick to other smaller particles. [low confidence]
- Unlikely for uncleaned filters to cause major backpressure issues and damage MVHR unit.
- Bacterial growth can occur on filter in 6 months.
  - Personally not so sure about this one. [will clarify next meeting]. Might be specifically a Netherlands thing, as mold is much less of a problem in my home despite the air being much more humid.
- Filter manufacturers want to change advice about vacuuming filters. Current popular advice is vaccuum once. This may change as filter manufacturers say that may damage filters
  - Personally, feels excessive. More details in interview with design consultancy.
- Newer devices can measure airflow through filter to give more accurate warnings to clean
  - Not sure how that would help personally. Flow rate does not account for air quality.
- Users liked filter with smaller width during testing. It was easier to insert and remove. I reduced width from 23mm to 15mm
  - It might be possible to reduce the width even further. That might be an extremely simple diway to make things easier with minimum possible effoer if it could be achieved by a process change or something.

Tim interview 2 notes [10 days after interview 1]

- supply filter, i.e. outside filter will not have dry air, though the return filter might. But that's not all that critical, because even if the return filter has mold, it won't affect the heat exchanger, or reach the users.
- Old device has a timer for filter clean (W01) and filter change (W02). Newer device will have volume based indication.
  - Tim did not know actual times for W01 and W02
  - Some other products measure pressure differential.
  - Could measure power draw or some other kind of metric. Itho has some devices that connect to the cloud and send data. Usually for servicing heat pumps, not typically ventilation systems.
- Re-evaluated mold growth in 6 months claim
  - Concluded that it is inaccurate. If mold growth can happen in 6 months, then when filter is rotated, then the side of the filter that is not active can still spread spores.
  - Personal thoughts: Mold growth may be the limiting factor, as if it is observed, then double filter must be replaced even if the other side is clean. Maybe double filter might not be the best solution for future iterations then. It is dependant on how soon mold growth occurs.
  - Based on communication with patrick and recommended filter change times in the manual, I speculate mold growth will not happen until well over a year.
- Surface area of filter affects air pressure. A smaller filter area corresponds to a smaller area for air to flow through. This means a greater mass flow rate. Which means greater pressure, which increases risk or air going around the filter and contaminants making it past.
  - Pleat size does not affect filtration too much. The main goal is to have filter area be as large as possible.

Tim interview 2 notes (contd)

- adding a backing strip is a manual job. Would add about 75 cents per operation.
  - Labelling backing strip would be easy, as they could be printed on the strips beforehand. No major cost increase. Tim found this would be a logical solution.
  - Printing on front face may be difficult. Need to ask their filter manufacturer if that is possible, since that is the pleat itself, which is a glossy surface.
- Shutting down device is critical, since dirt is not always on filter. Big things may fall down, and then get sucked into the machine if the airflow is on.
  - We agreed that nether residents, nor maintenance workers would actually pull the plug. A good option would be to have a 5-10 minute shutoff timer as part of the filter replacement routine. This could be easily implemented as a software update.
- Ideally the machine slot should also be cleaned. Not mentioned in manual
  - Personal thoughts: Maybe this can be fixed by using the rails as a dust tray.
- Rails system difficult to implement in both directions. MVHR units will be always touching the wall of the skid closest to the house to reduce ducting length. Due to the difficulty of accessing the filter points in the front orientaion, i believe Itho HRU 300 units will be installed in the reverse orientation only.
  - It is alright if the retrofit works only for a single orientation.
- Rails could be a retrofit accessory, to be installed for larger projects with 100-200 apartments.
  - There is already precedence, as filter doors for this unit are too tight and have been replaced for bigger projects before.
  - Need to take care of tolerances for retrofits.
  - Device already has guide rails on the inside for the filters that could be reused.
    - Personal thoughts: Final design of bracket is hard to tell without looking again at machine or a CAD file (which could not be shared). Still, I am confident it can be done.

Tim interview 2 notes (contd)

- Filter doors already create leakproof seal. Only thing to make sure is doors should close.
- Can put holes in bracket. As long as they do not majorly obstruct airflow it is fine.
- 30 to 40 cents could be the cost per bracket if injection moulded. This is considering the part is outsourced. Even cheaper if made in-house, which itho is working on setting up
  - Itho has in-house tooling, which can cost 20-30k euros for mold. However, I think if the number of units is not so high, they can use cheaper aluminium molds.

- New Itho product releasing in 2025. The decision to come up with a new product is made when there are enough marked questions and needs that can be resolved.
  - Cannot mention any details about the new design, except that it addresses many of the principles brought up by my advice.

Vacuuming filters

- Says filters should definitely be vacuumed. Does not affect them. Specifically for large visible debris such as fruit flies, insect parts, airborne seeds.
    - Seems logical to me. Based on my understanding, the vacuuming will only work for coarse particles (size>10microns), and if done gently, should not damage the fibers

Filter directionality

- Answer about Zehnder filters corroborated with Tim's answer. Confidence high.

Filter change duration

- Filter can be changed between 6-18 months depending on air quality. eg. Central London could be 3-4 months but that is an outlier. Claims that manufacturers might be overcautious with their 6-month recommendation, and 1 year is usually reasonable.
    - This could be true, but I personally do not think a social housing company would want to ignore manufacturer recommendations as that might cause liability issues. Also, NL and UK environment might be different.
- Mold growth does not happen in a year. This is because MHVR only circulates dry air. Could happen if machine is switched off for long periods of time
    - I don't understand how the air could be dry before it hits the filters, couldn't find much info about this.

- MVHR machines don't use a lot of power. About 0.5kwh/day. That can go to double or more with clogged filter. But the increase in power consumption is still not so high.
- Other issues could be increased fan strain, increased noise, dirtier air (esp due to mold)

- Geographic changes are very local. You can find major differences between an apartment of a building that faces south, and another that faces north onto a main road. This is because heavy particulates do not travel very far.

- Zehnder machines give a "check filter" warning every 6 months. Like check engine, it does not stop the machine from functioning [need to double check with manual]

- I asked if it would be possible to measure filter dirtiness by checking power draw or fan strain or some other value.
- It might be possible to connect a measuring device [recheck which one specifically] to the unit when fresh filters are input and see the power drain increase over time, and setup alerts
    - Personal opinion. This system works for homeowners, but since OEMs of MVHR units already have a lot of data, and units nowadays have wireless communication, this could be integrated in a much more sophisticated way.
- An sharp increase in power drain may also reveal other issues.
- For social housing, this system could be implemented in a few of the flats with the "dirtiest air", and a filter replacement for the entire building could be conducted using them as a baseline.

Eric notes

Modifying filters

- As long as cost increase is not too high idea can work. Suggestions are plausible
- An asymmetric filter design could be manufactured, ensuring it can enter in only one orientation.

Modifying device

- Cost to device could be higher. Perhaps more appealing to more premium companies.
- Moving components, especially sliding components in path of airflow might get clogged.
- Attempt to reduce obstructions to airflow.
- Consider leak tightness

Retrofitting

- Retrofitting is difficult in general, but certainly possible and has value for housing corporations. A single time retrofit could be combined with the standard maintenance operations to reduce the number of maintenance calls.
- Would be ideal if the retrofit does not require complete disassembly.
  - Personal thoughts: would also have to consider if the retrofit can be done by the maintenance crews or it must be done by OEMs. If it must be done by maintenance crews, the retrofit mechanism has to allow for a much greater margin of error.

General discussions about the mechanism