Appendices - Dynamic ventilation

Part of master thesis report – Marijn van Limborgh (4719964) – 30-04-2025

Appendix A – Project brief

Delft – 17-10-2024

Original personal project brief

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Adaptation of indoor climate controll systems for heat-pump installation

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Climate control in Dutch homes is usually centralized (Figure 1). One thermostat in one room controls the input for the climate system for the entire house. Whilst zone-specific / decentralized technologies exist for new homes, a similar system for climate control is expensive to implement in existing Dutch homes. Being able to control indoor climate per room/section could have interesting applications. Apart from saving on heating and cooling energy, adapting a system for this would allow it to be more useful combined with future smart home systems. If enabled to detect a person's presence in one room, it might allow for the climate system to focus on the rooms in use. Automating the process of turning on/off heating whilst keeping the desired temperatures according to the user's preset preferences. This could increase perceived climate comfort, whilst saving energy on controlling the climate of the house as a whole.

The project aims to design a decentralized addition to Joule Technologies' system. That helps to improve the transition of existing Dutch house heating systems to Joule Technologies' heat-pump system (Figure 2).

➔ *space available for images / figures on next page*

introduction (continued): space for images

Vocabulary

Climate control	Controlling heating, ventilation and cooling of indoor spaces.
Centralized system	A climate control system that has one control point, and does not differentiate output for different areas.
Decentralized system	A climate control system that allows for separate output of certain areas.
Controlled decentralized system	A climate control system that allows for separate output of certain areas and can control the output for these areas individually.

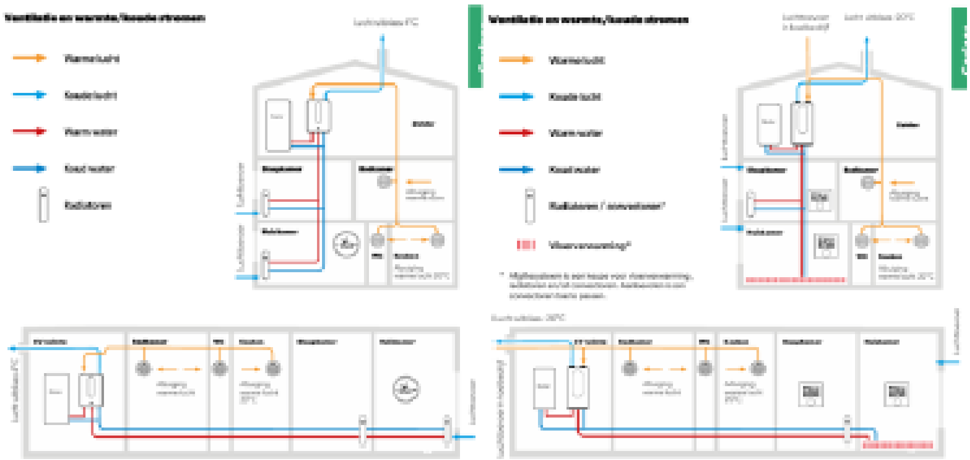


Figure 1: Centralized system on the left, controlled decentralized system on the right (Inventum Technologies, n.d.)

image / figure 1

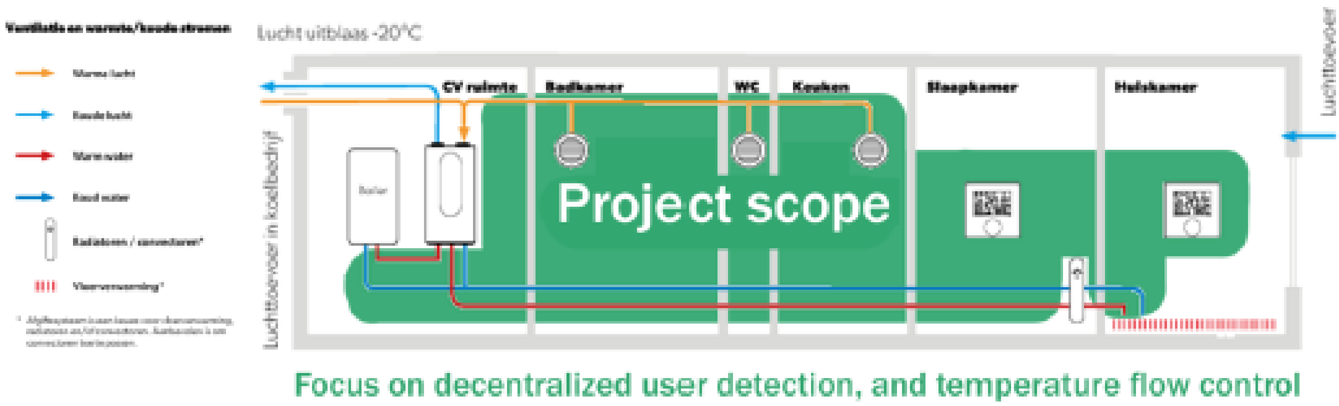


Figure 2: Project scope

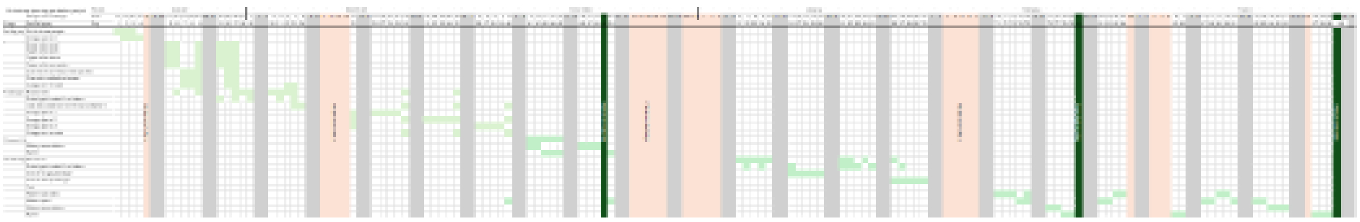


Figure 3: Project planning

image / figure 2

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Even though it might be possible to keep part of the system, adding new components to the system can negatively affect the system if not done right.

For the user replacing part of the system increases costs and the system's footprint, whilst the savings in required heating energy might decrease both. During this project a middle ground should be found between these two aspects for the changes proposed or the system should have other properties that would justify the system not being ideal.

Adding complexity to the system also directly impacts the difficulty in how to understand a system. Current heating systems often already are hard to understand or steer for users. Some might use one system as if it were the other, making the system less effective and or more polluting. Adding complexity, creates a similar problem for installation and repair. Although installation parties from companies understand their own systems, many 3th party repair companies / installers do not. Making the system easier to understand and control would be advantageous. This might create insights Joule Technologies can implement in future iterations.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Develop a controlled decentralized addition for Joule Technologies' new system to be integrated into existing Dutch Households. 'Future-proofing' them to be more sustainable through smart features.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

Explore current options available for users, the differences between new and old Dutch in-house climate systems and what might be integrated into future systems.

Identify bottlenecks in the existing system and find opportunities for improvement to make existing systems more suitable for heat pump installation and future smart home integration.

Develop and test the potential of some improvements to find areas most suitable for improvement, within the time frame and scope of this project.

Focus on one of them and develop a working prototype.

Appendix B.1 - Vakbeurs energie

Fair – Den Bosch – 16-10-2024

This appendix contains a summary of different conversations and presentations seen at the fair ‘Vakbeurs Energie 2024’ in Den Bosch.

Summary

(ChatGPT – checked)

Condensation is a key issue in construction, leading to water buildup, mold, and rust, especially with heat pumps. Heat pumps are most efficient in low to medium temperature ranges but may need gas kettles for higher temperatures. Different user types (housing corporations, private installers, contractors) handle heat pump installations differently. New buildings must be zero-emission by 2026, and existing ones by 2050, with insulation often more important than conversion. Installation can be noisy and complex, with brands like Honeywell offering efficiency improvements.

Key learnings

1. **Condensation:** Causes mold and damage if insulation is poor.
2. **Heat Pump Efficiency:** Works best at 20-50°C; gas needed for higher temperatures.
3. **Building Regulations:** Zero-emission standards by 2026 for new, 2050 for existing buildings.
4. **Flow control**: Brands like Honeywell improve efficiency with better flow control.
5. **Heat Pump Benefits:** Improves ventilation and climate control.

Notes & explanation

Building / construction issues

- Condensation is a big issue in the industry. This causes most issues surrounding construction adaptations and other items. When surfaces with a big temperature difference are not left in an open area, where condensation can escape, it can cause water buildup in constructions. This might cause construction elements to rot, cause mould or rust. For most air-air heat pumps the difference in temperature requires the in and / or output air channel to be insulated increasing conversion costs.
- 3 different emitting systems, divided by low (20-30deg), med (40-50deg) and high (60-70deg) temperature. Difference mainly dependent on amount of surface area available for transmitting heat. Some emitting systems have fans build in to increase airflow through the system. Lower heat heating systems take longer to heat and cool due to lower max power capacity. Heat pumps operate in ranges of low to med heat, after that it needs to be supplemented by a kettle. Kettle and heat pump can be placed in line, to reduce gas usage for first part of heating.

User types

- Housing corporations – Big clients that arrange houses for rent for large groups of people. They often provide service for a big group at once, and have their own maintenance crews. Users in these houses don't choose for heat pump installation themselves, and are often not interested to see how heat pumps work. Using them as if they were gas kettles. This causes complaints at housing corporations and inefficient use of the heat pumps.
- Private installers – Are interested in what the technology can do for them, often listen to the advise of installers on what to do. They do not always have all information, or work together with certain suppliers.
- Installers – Contractors that can ask production parties for information. They convert the buildings.
- Advisors – Separate advisory companies exist to provide detailed advise on insulation and house conversion. They often use software / hardware to look at possible issues in buildings.
- Production party – Makes products, support installers, but try not to get involved with individual users.

House types

- New buildings
    - 2026 – new buildings should be 0-emmision buildings. This means no building permits will be provided for houses that use gas heating.
    - Need to be insulated according to the standard norm
- Existing buildings
    - 2050 – All buildings should be running on 0-emmision systems for their heating.
    - Insulation is often more effective then conversion from gas power to heat pump

Competition

- Often work with external and internal parts of the system. This can cause noise complaints, and is harder to install. The distance between the inner and outer components is also limited based on the conversion gas.
- Honeywell has interesting solutions for steering liquids and passively controlling flow speed in radiators.
- Some brands use fans to improve radiator efficiency

Advantages of heat pump installation

- By forcing ventilation, and (sometimes) controlling air input temperature, the climate

Appendix B.2 - Interview Mark Leijtens

Business Developer & aftersales – Inventum – 22-10-2024

Summary

(ChatGPT – checked)

The interview highlights key challenges in the installation, sales, and after-sales processes for heat-pump systems compared to traditional central heating (CV) systems. The main difficulties stem from consumers' lack of knowledge on operating heat pumps, differences in system requirements, and varying performance based on building insulation and system design. Unlike CV systems, heat pumps work at lower temperatures, requiring larger pipes and emitters for optimal function. Buildings with inadequate insulation or substandard installations can exacerbate performance issues, particularly in low-cost housing, where cost-saving measures are common. The transition from CV systems to heat pumps often involves educating users, especially in housing associations where renters may not fully understand the technology.

Other challenges include ensuring proper system design, insulation, and user understanding. Buildings with older pipe systems or inadequate emitters may need hybrid solutions that combine heat pumps with CV systems for additional heating. Users' preferences, influenced by factors such as age, cultural background, and lifestyle, can also impact heat-pump performance and the overall user experience. Maintenance is typically minimal but essential for optimal operation, with annual checks and air duct cleaning recommended.

Key learnings

1. **User understanding**: Consumers, especially renters, often struggle or don't take the time to understand heat-pump systems. Many people are unfamiliar with the technology and may find it challenging to adapt their behaviour accordingly. Users need to be educated by the retailers on the use of heat-pumps, which does not always happen.
2. **System Design Differences**: Heat-pumps require lower temperatures, larger pipes, and efficient emitters compared to CV systems. This leads to challenges in older or poorly designed buildings.
3. **Hybrid Solutions**: In older buildings, hybrid systems combining heat pumps with CV installations are often used to work with the requirements of in-house radiators that require higher temperatures.
4. **User Preferences**: Older people and those from warmer climates may prefer higher indoor temperatures, which can strain heat-pump systems and complicate energy efficiency. This can cause uses to be unhappy with the installation.
5. **Housing corporation:** Don't want users to have too much data, as they then get called with a lot of questions on items previously untreated by the users (ex. CO2 measurements).

6. **Check out EPC & BENG:** It might be useful to create a model based on the BENG requirements which I can place different ideas in to test them against each other.
7. **Complimentary heating:** Spaces that might have different temperature requirements then the rest of the house, like the bathroom. You can choose to place a small electric radiator there, to make sure you don't need to keep the entire house on the same temperature.

Appendix B.3 - Interview Jean Paul Vonk

Manager Product Management – Inventum – 24-10-2024

Summary

Summary: (Chatgpt – checked)

The interview primarily discussed heating and cooling systems, with a focus on heat pumps, radiators, and floor heating systems. It covered the challenges and solutions related to zone-specific heating and cooling, particularly in terms of efficiency and responsiveness. The conversation also highlighted the integration of new technologies into product offerings, such as digitalization, user-friendly interfaces, and automation, particularly with BEN (a heat pump system under development). The discussion explored potential product expansions, how data from these systems can be utilized for both consumers and businesses, and the importance of maintaining efficiency and user-friendliness. Several challenges in system retrofitting for existing homes were addressed, alongside the potential for preventative maintenance and smart systems to improve user experience.

Key learnings

1. **Zone-Specific Heating Challenges**: Heating and cooling responsiveness in rooms based on occupancy is difficult due to system delays (especially with floor heating).
2. **Decentralized solutions**: Combining heat pumps with other systems like electric heaters or fan coils can improve efficiency or user comfort.
3. **BEN as an environment**: BEN is being developed as a health & comfort-focused environment that can help people Become Energy Neutral. Aimed at offering a total solution, including thermostats and sensors, while maintaining efficiency.
4. **Digitalization and Data Usage**: There is a focus on integrating monitoring and data collection into the system, especially for commercial purposes. However, a challenge lies in making this data meaningful for users (e.g., through cost savings, maintenance warnings or energy use visualization).
5. **Preventative Maintenance**: Opportunities exist for predictive maintenance based on data trends to inform installers and improve system reliability.
6. **Challenges in Retrofitting**: Installing new systems like heat pumps in older homes poses challenges, particularly regarding ventilation and compatibility with existing infrastructure. This is why Inventum mainly focuses on houses build in or after the 80s, as they are regulated on ventilation.
7. **Smart System Control**: There is potential to improve efficiency by designing smarter thermostats or control systems that limit user intervention, aligning with how heat pumps operate efficiently.

Appendix B.4 - Interview Rogier Donkervoort

Contingentenaanpak – TNO – 07-11-2024

Summary

Summary (ChatGPT):

The *contingentenaanpak* (contingent approach) refines sustainable housing solutions by categorizing homes based on specific features, such as roof structures and heating systems, rather than general archetypes. A detailed database, built with both public and private data, uses visual AI tools to classify building characteristics and predict the feasibility of sustainable technologies like heat pumps.

The approach involves:

1. **Data Collection**: Installers log building details and outcomes of installations, enhancing data accuracy and prediction models.
2. **Pilot Projects**: Testing includes AI-assisted assessments of heating systems' compatibility with heat pumps.
3. **Success Metrics**: Currently focused on installation feasibility and compliance with standards, with potential for expanded metrics like customer satisfaction.

Heat pumps are viewed as cost-effective for many homes, though hybrid systems may suit higher hot water demands. District heating (warmtenet) faces criticism for reliance on fossil fuels and higher long-term costs.

This reversed approach—identifying homes based on solution requirements rather than fitting solutions to homes—could support a nationwide system where residents can identify compatible sustainability solutions for their specific property. Data consistency and public acceptance are critical for scaling this strategy.

Key learnings

1. Challenges in Standardizing Sustainable Housing Solutions
    - Initial attempts to create standardized sustainability solutions for common housing types often failed due to unexpected variations in buildings.
    - The Netherlands may require different solutions for each house, but some houses can still be categorized effectively.
2. Development of the Contingentenaanpak (Segmentation Approach)
    - A database was built to classify buildings based on specific characteristics to identify suitable sustainability solutions.
    - Data sources include public and private information, along with AI-assisted visual analysis (e.g., recognizing roof indentations).
3. Use of AI and Data Collection for Heating Systems
    - A project explores using installer-submitted images of heating systems to analyze compatibility with heat pumps.

    - AI could help extract relevant details from images, improving future upgrade recommendations.
4. Defining Success in Sustainable Installations
    - Contractors determine success based on whether the installation works for both users and their processes.
    - A “building DNA” approach helps define which building features contribute to successful sustainability projects.
5. Proactive vs. Reactive Sustainability Planning
    - Instead of assessing houses individually, the approach first identifies successful sustainability solutions and then finds matching houses.
    - Success is primarily measured by installation feasibility rather than long-term efficiency or customer satisfaction.
6. Pilot Project in North Holland
    - Targeting specific houses instead of all homes increased project success rates by 25%, reducing costs and improving efficiency.
    - The project provides proof of concept, but further validation is needed.
7. No Preference for Heat Pumps, but Practicality Over Heat Networks
    - The focus is on identifying applicable solutions rather than preferring heat pumps over alternatives.
    - Heat pumps are often more cost-effective and environmentally friendly than heat networks, which still rely on fossil fuels.
8. Challenges with Heat Pump Adoption
    - User behavior significantly impacts efficiency, but it is not a core focus of the current strategy.
    - Some demographic factors (e.g., elderly residents or large households) may influence energy use and should be considered in planning.
9. Importance of Accurate and Shared Data
    - Data collection remains a challenge due to inconsistent documentation by installers.
    - A structured database with categorized “yes” or “no” suitability assessments can improve decision-making.
    - Greater data sharing across stakeholders would enhance the effectiveness of the transition to sustainable heating.

Appendix B.5 - Interview Tom van den Berg

Sensors and PCB components, requirements and prices – Joule Technologies – 24-01-2025

Key learnings

eCO2 (VOC) vs CO2 sensor eCO2 costs 2eur, CO2 20eur

VOC sensor is not very accurate, CO2 sensor is

For new buildings accuracy is required for legislation. They are currently testing VOC sensors for their thermostats.

Communication through zigbee, also advantageous for loose future products.

Extra advantage of wireless is that certification for electric devices is much easier and cheaper.

If connected to an outlet, the product needs an adapter. This can also be build into the product, although this makes certification much more expensive and requires more space on the PCB and the components on the PCB to be higher.

Connecting the battery or plug to the PCB should be done by 2 attachment points attached with screws, so the plug does not require a large path where air goes by.

It'd be advantageous if the entire system can be connected together through the ducts to one adapter / input point. This would decrease adapter costs by quite a lot.

The placement and openings in the PCB housing is suitable for the sensors

COe sensors might be interesting, but they degrade fast. Therefore it might not be suitable for such a product, unless it'd be easily replaceable.

Unless CO2 sensor is used. A battery powered version, with the right settings, 1 AA battery can most likely be used for 1,5 years.

Making a battery rechargeable does not add value for the product. Using a standard AA or AAA battery is most likely the most affordable way.

Components on the PCB:

- 1 chip, most likely enough
- Battery+voltage increaser / plug +Adaptor
- CO2 sensor / eCO2 sensor
- Stepper motor
- Other components

Electronics costs (3000 pieces) (With a higher amount, prices will drop rapidly)

- About 30-35 eur with VOC sensor
- About 18eur extra for a co2 sensor

- With co2 sensor it'd need to be wired and have an adaptor, raising the total price to 50-60eur

Appendix B.6 – AI Interview

ChatGPT-API – Digital – 04-11-2024

During the course EDI through an exploration of AI opportunities in the design process I concluded that enhancing the realistic responses of AI language model ChatGPT 4.0 can be done by expanding prompts in a certain way. Here I retrieved more interesting answers by letting one chatroom interview another one, whilst providing both with prompts. After I made the model in Jupyter Notebook to be able to use in future projects. This model was made to be interviewing a multiple of these enhanced chatbots and making ChatGPT summarize its own results (Figure C01).

During this test I outputted both the entire conversation and the summaries.

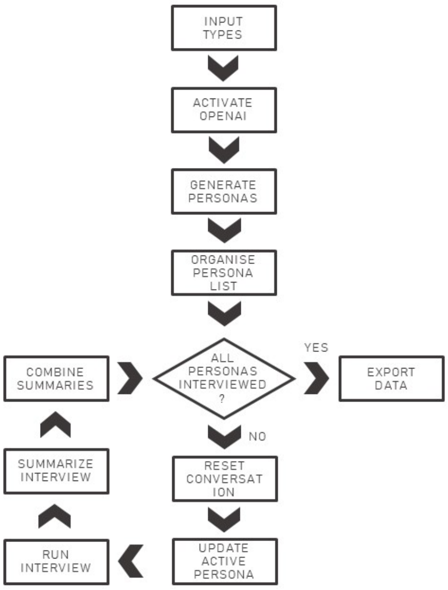


Figure C01: Code layout

Prompts

persona_amount = 10

situation = 'resident in Rotterdam.'#Formulate as follow up to following line: Generate [persona_amount] personas of people [situation]

interviewer_type = character_bot1 = "Bot 1 is a friendly and curious interviewer, who wants to know more about how people use their thermostat. The interviewer tries to keep the conversation about the topic of the heating system. The interview prepared the following questions: [Question 1] What type of heating system do you have, and what temperature do you set your thermostat? [Question 2] What do you find important about your heating system? [Question 3] How do you control your heating system? [Question 4] How do you adjust your heating system? [Question 5] Is your heating system often adjusted by others then yourself? [Question 6] Would youy heating system to be automated? [Question 7] Do you feel like you have control of your heating system? And if yes, what makes you feel like you have control of your heating system? [Question 8] Do you understand your heating system? If yes, what makes you understand your heating system? If no, what do you find to be unclear about your heating system?"

assignment = 'Summarize the needs about indoor heating systems from the participant into one list:' + chatlog

Conclusion

Here's a consolidated list that combines sets of requirements for an ideal indoor heating system, covering aspects of efficiency, control, user convenience, and environmental responsibility:

1. **Energy Efficiency and Cost-effectiveness**: Prioritize energy-efficient systems to reduce utility expenses and environmental impact while balancing upfront and ongoing costs.
2. **Reliability and Durability**: Opt for systems known for consistent performance, long lifespan, and minimal maintenance requirements.
3. **Quick and Consistent Heating**: Ensure the system can rapidly heat spaces and maintain a stable, comfortable temperature without fluctuations.
4. **Comfort and Control**: Provide customizable temperature control, allowing users to set schedules, zones, and manually override settings as needed.
5. **Programmable and Smart Thermostat Options**: Include programmable schedules and smart thermostat capabilities for automation, convenience, and potential energy savings.
6. **Remote Access and Smart Integration**: Enable system control from any location through apps and compatibility with smart home devices.
7. **User-Friendly Interface**: Ensure an intuitive and easy-to-navigate interface for straightforward adjustments and operation.
8. **Feedback and Usage Insights**: Offer detailed reports on energy use and savings recommendations to improve efficiency.
9. **Environmental Responsibility**: Choose systems with low carbon emissions and compatibility with renewable energy sources when possible.
10. **Ease of Installation and Compatibility**: Ensure new systems are compatible with existing infrastructure and easy to install.
11. **Customization and Shared Control Features**: Provide flexible options for multiple users to adjust settings in shared spaces and suit personal schedules.
12. **Basic System Understanding and Troubleshooting**: Encourage users to gain a basic understanding of the system's operation for simple troubleshooting and maintenance.

In summary, the ideal heating system combines efficiency, reliability, control flexibility, smart features, and ease of use while being cost-effective and environmentally conscious.

Appendix D – Context

Describes the field and information the project is built upon

What do we need to know?

- What type of systems exist?
- Who are the stakeholders?
- Where are systems installed?

What type of systems exist?

In Dutch houses gas powered heating systems are primarily used, with All-E (All electric) heating systems steadily on the rise (Table D01). Gas powered systems will decline over time, as gas prices in the Netherlands are rising due to closing of the Dutch gas reserves in 2024. The government is also pushing for more All-E solutions, making it mandatory for new building permits in 2026 and requires existing buildings to convert by 2050 (Appendix B) (Rijksdienst voor Ondernemend Nederland, 2022).

Type	Share in Dutch houses 2022 (%)	Growth 2019-2022 (%)	Output temperature (°C)	Note
Gas	87	-2.1	75-85	
District heating	6.7	11.5	65-85	Heat-pump grants often denied in these areas
Gas + heat-pump	1.1	83.3	45-55	
All-E (Heat-pump)	2.3	187.5	35-45	Primarily heat-pumps, sometimes combines electric systems
Unknown	2.9			

Table D01: Types of heating systems in Dutch houses (*CBS Statline*, z.d.) (Appendix B)

Different heating systems have different temperatures at which they run efficiently (P. van Oostrom, personal communication). To use these temperatures effectively there also are different emitting systems (Figure D02). Mainly different in the amount of surface area that can be used for transferring energy and the flow volume in heating pipes (Doornbos et al., 2019) (Steenbekkers & Scholte, 2019) (Appendix B).

Type of emitter	Operating temperature (°C)	Note
Radiator	60-70	Depending on the size of the emitter it might also be usable on slightly lower temperatures
Convector panel	40-50	
Floor-heating	20-30	Reheating is inefficient, constant heating is desired
Self-powered	-	E.g. electric panels, infrared panels

Table D02: Types of emitters (Appendix B1)

Some companies also implement zone-specific heating, which can be efficient for bigger buildings and houses with insulated barriers (E.g. insulated walls and floors) between zones. For heat-pump systems this can be more efficient as less energy has to be provided in total. In Dutch houses barriers are often not insulated, sometimes making this solution less efficient as less emitting contact area is used to heat multiple rooms.

For creating a comfortable and healthy climate, ventilation is important. Too much ventilation can cause dry air and increases energy costs. Too little ventilation can be unhealthy (Appendix F). Optimising ventilation can increase comfort, air-quality and decrease energy consumption. The primary market focus for energy system upgrades is on efficient heating and insulation. However, ≈43% of total energy loss in insulated houses is caused by ventilation (Appendix C). With house insulation constantly improving, optimizing ventilation becomes more interesting.

Who are the stakeholders?

From design to installation, use up to discarding, many stakeholders have influence over the design and use of ventilation systems. In this part the most important ones will be discussed (Figure D05). The government/municipalities are mainly influential on a financial legal level. Financial influence often comes in the form of grants, which change a lot over time. The influence of laws is discussed in Appendix E and can be seen in the earlier discussed push for All-E systems (Rijksdienst voor Ondernemend Nederland, 2022). The government will therefore not be taken into account in this section.

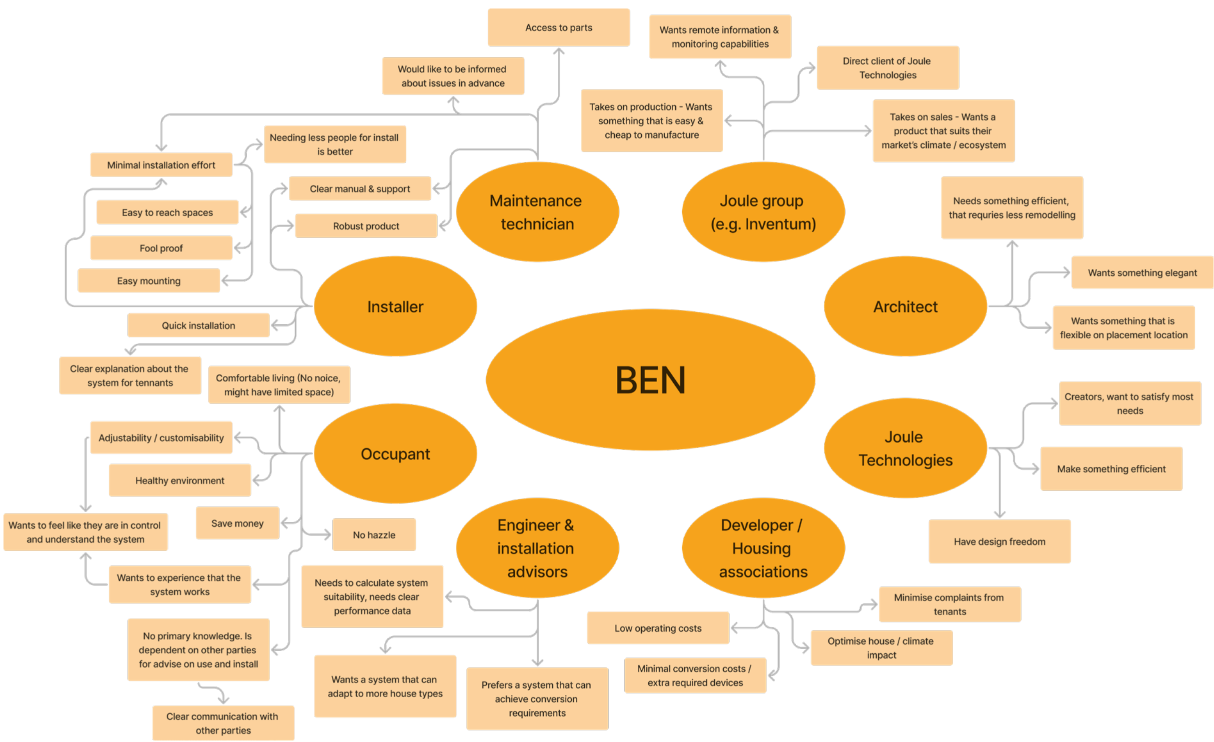


Figure D05: User groups in Joule environment (Veltman, 2022) (S. Haenen, Personal communication, 2024) (Appendix B)

The HVAC industry is highly technical, leaving most occupants unable to choose products independently. Private buyers often depend on local handymen for recommendations, while housing developers typically decide for larger projects (Appendix B). As a result, most companies design their product focused on these groups. Focusing on efficiency, ease of installation, and cost. Innovations in user control often rely on smart-home gadgets or thermostats aimed at tech-interested users. Most housing associations do not want to include detailed information about air-quality to occupants, to avoid extra work from people asking them what this means (Appendix B). This focus has led to limited innovation in effectively communicating how heat-pumps work to end users.

Where are systems installed?

Currently most heat-pumps are placed on property boarders, as they tend to be loud. Although ventilation heat-pumps are much more quiet, as they need to be place in the house. Sound still can be an issue for users and neighbours, which is an obstacle for some potential users to transition (Reinders, 2020). Ventilation heat-pumps are often installed in-house, where condensation can be an issue. Caused by high temperature differences between air in tubes and the surrounding air, condensation can lead to mould or property damage (Appendix B). Therefore, tubes with air from the heat-pump exiting the house should be insulated.

Controll systems are often installed on walls or devices (E.g. mobile phones) whilst ventilation and heating tubes and pipes are placed into or along the wall/ceiling. Inside walls there is limited space, with minimal thickness for walls containing ventilation channels having around 9cm available for tubing (K.J. Veltman, personal communication).

Analysis of existing products

Products that steer total climate

Steering indoor climate is usually done with thermostats. Some thermostats can be programmed to temporarily or automatically change temperature. Others can be controlled from distance and connected to smart home applications. In this category some variants also try to learn from the user and adjust settings automatically.

Advantages

1. Thermostats are easy to use
2. Smart applications give more insight and control

Disadvantages

1. Users often are not informed how to most efficiently use the system
2. 'Smart' thermostats and applications sometimes have an adverse effect as they are not aware of when the heating installation is most efficient
3. Smart applications are not used by the average user

In conclusion, due to the variety of systems, products are often not aligned properly. A subdivision of complicated information on the app, and general information for the average user on the thermostat would be advantageous. Currently information about how to operate the system is not intuitively presented.

Figure 2.1: From left to right, thermostat, digital thermostat, smart thermostat, app.

Products for energy subdivision

Traditionally knobs have been used to manually adjust flow to emitters. Later knobs contained mechanisms that closed the flow at certain room temperatures. Currently companies make knobs that can be connected to a smart home system. Alternatively division stations exists with constant, semi-controlled and smart system integrated versions.

Advantages

1. Knobs allow for focussing energy towards certain areas
2. Knobs can be replaced individually
3. By adapting the climate with knobs the effect of the change is easy to understand for occupants

Disadvantages

1. Dutch residences often have no insulation between walls. Heating the entire residence with less emitters can be inefficient at low operating temperatures
2. Climate system calibration can be thrown off by closing part of the system, making the system act differently than expected

In conclusion, clearly labelled/placed knobs and dividers inform users well. They can be used to upgrade systems, making them more efficient without the need to replace other parts in the system. However, they are prone to system interruptions/inefficiencies due to a lack of user-understanding.

Figure 2.2: From left to right, knob, smart knob, pipe flow division station

Products for better/easier installation

Issues surrounding installation can be caused by improper calibration of heat-pump systems and user error. Companies improve this by making knobs and line split points that adapt to differences in pressure.

Advantages

1. Pressure independent knobs and split points make infectivity due to user error less influential
2. Thus decreases the accuracy required when calibrating the system

Disadvantages

1. Variety of product types in this category is limited
2. As constant heating is efficient for heat-pumps, not drastically adjusting the temperature system often is more efficient. Thus if users are properly educated this loses functionality.

In conclusion, although this is an interesting category for further development. For Joule it might not be as relevant.

Figure 2.3: Various pressure independent connectors

Products that improve the rate of convection

When retrofitting systems to lower working temperature, emitting devices such as radiators might need to be replaced. Replacing infrastructure can be expensive and cumbersome. Ideally the emitter would be replaced by a larger radiator or floor heating. If space is not available there are other solutions. For example, increasing surface area or forcing more air through emitters by adding fans to the bottom. Recently a radiator was announced that uses similar heat-transfer principles as heat-pumps to transfer heat towards the convection area.

Advantages

1. Emitters can be replaced individually
2. Adding fans seems like a cheap way to increase convection speed

Disadvantages

1. These products are dependent on the rest of the system
2. Companies adding fans to radiators claim high increases in efficiency values that do not seem to match with the behaviour of larger companies scarcely adopting the technology.

In conclusion, although these products could be used individually, they are an extension of the rest of the climate system. They should be chosen based on details from the climate system, not the other way around. Joule does not develop these products.

Figure 2.4: From left to right, convector panel, heat-transferring radiator, fan

Products that improve air quality

HVAC companies can add filters to their products to treat air with the goal of creating a healthier and more comfortable climate. Recently, products to improve air quality are used more. These are products like air-purifiers, humidifiers, dehumidifiers or products releasing scent.

Advantages

1. Create a better indoor climate
2. Affordable

Disadvantages

1. Products often work on inaccurate sensors
2. Effectivity is dependent on user placement
3. Some products can negatively impact air quality when overused

In conclusion, integrating some of these products' attributes into the Joule environment would majorly strengthen their position on creating a comfortable and healthy environment. When the Joule environment has area specific sensors, they could be used to more accurately steer products.

Figure 2.5: From left to right, air-purifier, humidifier, dehumidifier, scent sticks

Products that inform users

Informing users is often done on the thermostat or through applications. Some who want more and/or more accurate data can buy air-quality measurement devices.

Advantages

1. More awareness about air-quality from user
2. Could be coupled with other devices

Disadvantages

1. Only interesting for certain users
2. Do usually not trigger improvement directly

In conclusion, although interesting for some, the average occupant doesn't really care for and/or does not understand results.

Figure 2.6: From left to right, thermostat, application, low and high end air-quality sensor

Products that direct ventilation

In insulated residences energy loss through ventilation causes the largest part of the energy bill (Appendix C). Companies solve this by adding HRUs (Heat Recovery Unit) to ventilation systems. These recover heat and blow it back into the residence. In newer residences, companies install systems that measure air quality and adjust required flow of ventilation accordingly.

Advantages

1. Adapting ventilation can increase air quality
2. Adapting ventilation can decrease energy loss

Disadvantages

1. HRUs only work with balance ventilation
2. Retrofitting existing residences with dynamic ventilation is expensive
3. Retrofitting existing residences with dynamic ventilation causes disturbance for occupants
4. Dynamic ventilation requires control points and boxes to be installed, making the system complex

In conclusion, using vented air more efficiently, and venting less air could greatly increase system efficiency and air quality. Although ideal for newly build residences, products on the market require a lot of investment and rebuilding to implement into existing residences.

Figure 2.7: From left to right, HRU, sensor control point, smart valves, ventilation boxes

Appendix E – Desired ventilation behaviour

A brief description of the issues specific to this part of the project

What is the problem?

Venting a house by using one ventilation group wastes a lot of energy.

To make the BEN environment a healthy and comfortable system/environment, multiple parts should work together to optimize the in-house climate.

The Dutch population should use less energy, and will be required to have an all-electric climate control system by 2050. For existing houses energy losses through ventilation become more important.

Who has the problem?

Residents wish for a decrease in energy costs and wish for a more comfortable in-house climate.

Joule Technologies wishes to distinguish themselves, having an options for creating a system of products that increase environmental health.

The Dutch government wants to encourage a decrease in energy consumption. Ventilation is the biggest source of heat-loss in existing Dutch insulated houses with ventilation type C. Ventilation type C is applicable for roughly 2.1 million Dutch houses (RVO, 2022).

Assignment

Develop a **controlled decentralized addition** for Joule Technologies' new system to be used in **existing Dutch Households**. **'Future-proofing'** them to be more sustainable through smart features.

What are the relevant factors?

- Public perception of the Become Energy Neutral system
- Perceived climate comfort
- Ease of installation
- Return on investment
- User understanding

Goals

1. Create a healthier and more comfortable in-house climate
2. Reduce required heating energy
3. Require minimal installation effort

4. Control the system for the user, whilst keeping them informed

How to achieve the goals?

- Find a way to sense the status of air
- Make a network of valves that can steer flow by selectively blocking it
- Decrease the amount of unnecessarily displaced air by, optimizing it for the user, whilst keeping them informed.

What are the side effects to be avoided?

- Noise should not be a nuisance to the occupants
- Avoid unnecessary obstacles or extras that increase required pressure differential or reduce reliability
- The system should be easy to clean and not obstruct ventilation tube cleaning

How to achieve this?

Currently, steering flow of the ventilation system is done by opening all valves in the system completely (Figure E01). Then, the ventilation unit ① is set to its maximum capacity. the valve ② closest to the ventilation unit is then calibrated to block the right amount of air. This is repeated for every valve that comes after in order of distance from the ventilation system. To improve air quality for each valve individually and minimise the energy loss through ventilated air, the system needs to be dynamic. Meaning flow can be adapted continuously for each valve.

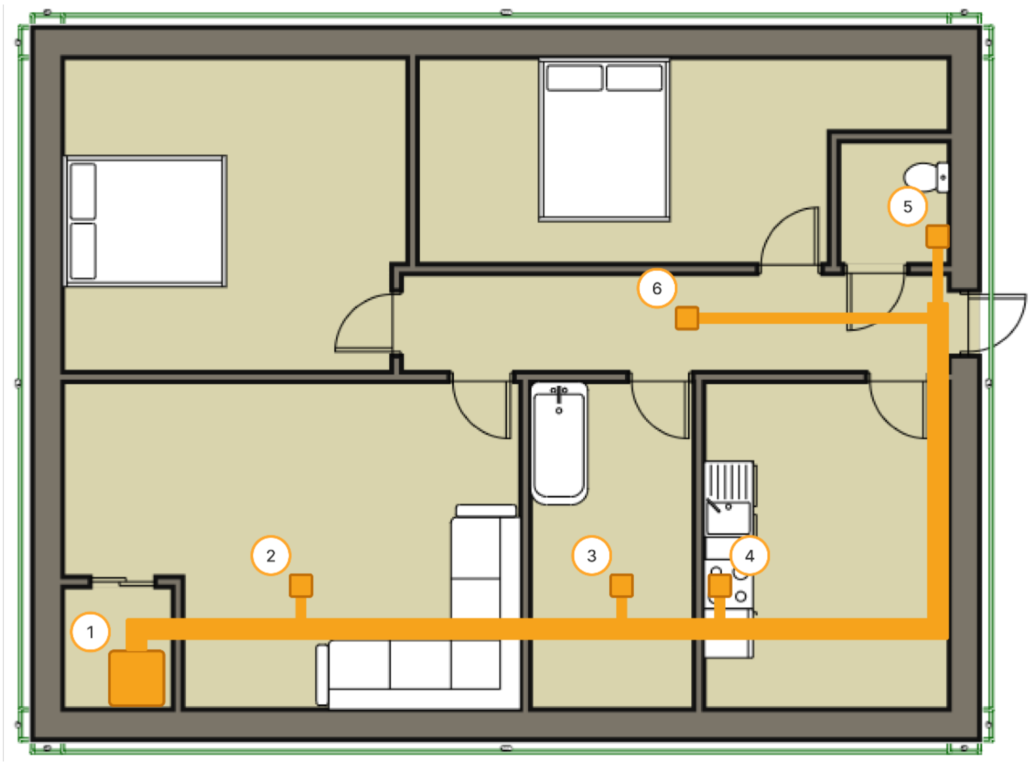


Figure E01: Ventilation system layout example

To steer flow, the system must control how far a valve is opened. For example an increase of flow / opening valve ② would cause a decrease of flow in the rest of the system. For this example this can be compensated by increasing the total flow from the ventilation unit ① at the same time, keeping the rest of the system stable. For this an active valve is required (Figure E02)

However, using an active valve at ④. Increasing the total flow could stabilize valves ⑤⑥, but would increase flow at valves ②③. Thus, when opening valve ④, valves ②③ need to be closed slightly to keep the total flow equal. If the area of ②③ are non-living / non-critical areas, doing this with an active valve would make the system expensive. Thus, it'd be beneficial to have the option to insert a constant flow valve (Figure E02) for some areas earlier in the system. Later in the project the choice was made not to continue exploring a constant flow valve. Due to low production quantities this valve will not be much cheaper to produce and a constant flow valve would make the system less efficient. If the system is rolled out and there are locations a constant flow valve is deemed useful, using one that is already on the market with the BEN name is more viable.

At the end of the system, a passive valve might be sufficient for one or more valves, as the flow can be adapted by the earlier active valves. These valves can be calibrated as usual by the installer, by placing the dynamic valves in the 0 position. For this the existent valves in the house most likely suffice. For new houses / owners who want similar looking valves, these should be added to the system (Figure E02).

In case the total pressure in the system is not enough, or it's required to be very high, it might be useful to add an fan supported valve / fan to the system. This has been looked at in the beginning of the project. However, it was determined that this is not necessary for a 1 house system like BEN. As the BEN has more than sufficient flow capacity to steer all fans in the target houses.

	Valve types			
Version	Active	Constant flow	Passive	Fan supported
Example				
Purpose	Ventilated living / critical areas	Ventilate non-ciritcal non-living spaces	Ventilate left-over areas / end of system	Ventilate living / critical areas that cannot easily be steared by the active valve
Mechanism	Adaptable air passthrough area, steerable by servomotor	Adaptable passthrough area, steerable by air-pressure	Manually adjustable passthrough area	Ventilator, driven by motor
Communication	Humidity and CO2	-	Humidity and CO2 (Optional)	Humidity and CO2
Notes	This system can be noisy, especially when close to the room			BEN can provide enough flow for all valves in a house

Figure E02: Valve types *critical area could be laundry spaces, or other humid areas

Therefore, the rest of this system will focus on creating an extension to the system using the Active and Passive valves.

Is this allowed?

For existing buildings the minimum flow values that need to be reached for each room when maximum flow is requested by the system is indicated in Table E03. These values are determined by the Dutch building law (Rijksoverheid, 2024) and the NEN 1087 norm (NEN, 2020).

Dutch building requirements Type of area	Required flow capacity	Value
Living area		
Minimum	25.2	m3/h
>10m2	2.52	m3/h/m2
Living area (With stove)		
Minimum	75.6	m3/h
>30m2	2.52	m3/h/m2
Bathroom		
Minimum	50.4	m3/h
Toilet		
Minimum	25.2	m3/h
Utility room		
Minimum	7.632	m3/h/pp
Containing garbage		
Minimum	36	m3/h/m2
Utility room (Containing gas infrastructure)		
Minimum	7.2	m3/h
>2m2	3.6	m3/h/m2
Parking space for vehicles		
Minimum	10.8	m3/h/m2

Table E03: Minimum flow values that the ventilation needs to be able to reach in Dutch existing homes

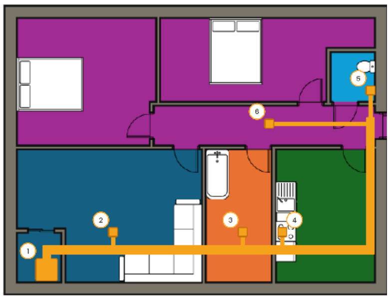
Often not all rooms are used at the same time. The total minimum ventilation is required to be sufficient for the room with the biggest ventilation need that is attached to the ventilation system. The total required ventilation does not have to be the sum of the necessary capacity (Rijksoverheid, 2024, article 3.67 lid 4 Bbl).

In the regulation no description is given over automation requirements per room. In its current form, although the total requirements needs to be reached when installed and set to maximum. Ventilating less in areas seems to be permitted as long as maximum ventilation is possible. If this is changed in the future, using passive constant flow valves is not possible due to being unable to guarantee minimum flow when in use.

Active flow valves need to be adjustable / have an installation sequence. So the system knows what position to return them to when maximum flow is requested from all valves. This position is in the rest of this report called the 0 position. How this should be done is discussed in Appendix G.

Desired behaviour (Example scenario)

Although the total ventilation flow should never dip below the total minimum, this minimum amount should be set and measured in the BEN. When all valves request maximum ventilation flow, they should be rotated to their predefined set position by the installer creating a normal maximum flow situation. When not all valves request maximum flow, they can be adapted to prioritise certain valves as described in the section "How to achieve this?". This next section will describe what flow situation would be preferred in certain situations. To do so an example scenario has been created (Table E04 & Figure E05).



Situation with dynamic ventilation										
Living area		Size (m2)	Valve type	Required possible ventilation	Sleeping	Taking a shower	Having breakfast	Leaving for work / school	Making dinner	Chilling on the couch
Living room		20	Active	50.4	10	10	10	10	10	30
Bathroom		8	Active	50.4	20	50.4	30	30	20	20
Kitchen		12	Active	75.6	10	10	40	20	80	15
Toilet		2	Active	25.2	10	10	10	10	10	10
Storage room		2	None	7.632	3.75	0.5	0.5	0.5	0.5	0.5
Hallway (also storage room and bedrooms)		8	Passive	15.264	75	10	10	10	10	10
Bedroom 1		14	None	35.28	35.625	4.75	4.75	4.75	4.75	4.75
Bedroom 2		16	None	40.32	35.625	4.75	4.75	4.75	4.75	4.75
Total minimum		75.6	-	75.6	75.6	75.6	75.6	75.6	75.6	75.6
Total		82	-	300.096	125	90.4	100	80	130	85

Original situation										
Living area		Size (m2)	Valve type	Required possible ventilation	Sleeping	Taking a shower	Having breakfast	Leaving for work / school	Making dinner	Chilling on the couch
Living room		20	Passive	50.4	20.99328	51.5595	20.99328	20.99328	51.5595	20.99328
Bathroom		8	Passive	50.4	20.99328	51.5595	20.99328	20.99328	51.5595	20.99328
Kitchen		12	Passive	75.6	31.48992	77.33925	31.48992	31.48992	77.33925	31.48992
Toilet		2	Passive	25.2	10.49664	25.77975	10.49664	10.49664	25.77975	10.49664
Storage room		2	None	7.632	4.102687	10.0762	4.102687	4.102687	10.0762	4.102687
Hallway (also storage room and bedrooms)		8	Passive	15.264	41.02687	100.762	41.02687	41.02687	100.762	41.02687
Bedroom 1		14	None	35.28	18.46209	45.3429	18.46209	18.46209	45.3429	18.46209
Bedroom 2		16	None	40.32	18.46209	45.3429	18.46209	18.46209	45.3429	18.46209
Total minimum		75.6	-	75.6	75.6	75.6	75.6	75.6	75.6	75.6
Total		82	-	300.096	125	307	125	125	307	125

Notes	
Occupants	2
*Total minimum is determined by the ventilation capacity of the biggest ventilated space. So it does not need to be the total	
*Unless otherwise indicated, values are in m3/h	
*Rooms without valves are ventilated passively by flow through other rooms. In this case it is assumed the hallway valve flow attracts that flow	
*Constant will most likely fluctuate with +-6 depending on total ventilation request. When passive valve further has lower flow, the maximum value of the passive valve will be taken into account	
*In houses without 2 way ventilation, natural ventilation will occur slightly, and therefore contribute to the total ventilation	
*The values of these datapoints are estimated based on one room being used at any time for dynamic ventilation, and the ventilation settings only changed by the user when cooking or showering for the original situation	

Table E04: Desired example scenario

For the original situation the valves have been set at the highest required ventilation volume (300), and the flow valves have been set to divide this volume to the right rooms. The total flow of the original situation has been categorized into 3 setting possibilities, as this is usually the case with older Dutch houses. For this example the assumption is made that 1 (125m_3/h) will usually be used, and 3 (307m_3/h) will be used when showering and cooking.

For the dynamic ventilation example the assumption was made that one room was used at any given time for certain actions. In reality a combination of rooms will most likely be used, and request some form of ventilation, creating a higher ventilation request in some situations (Cooking and showering). In others this might even out (e.g. the same level of CO_2

is produced and removed, just in different rooms, both with half the required ventilation capacity). In this example the assumption was made that air would be refreshed in accordance to the per room minimal requirements when used. However, the total required flow to keep CO_2 and rh% levels acceptable will in most situations not be reached by the system, requiring lower ventilation levels for most activities.

Desired behaviour (Example scenario conclusion)

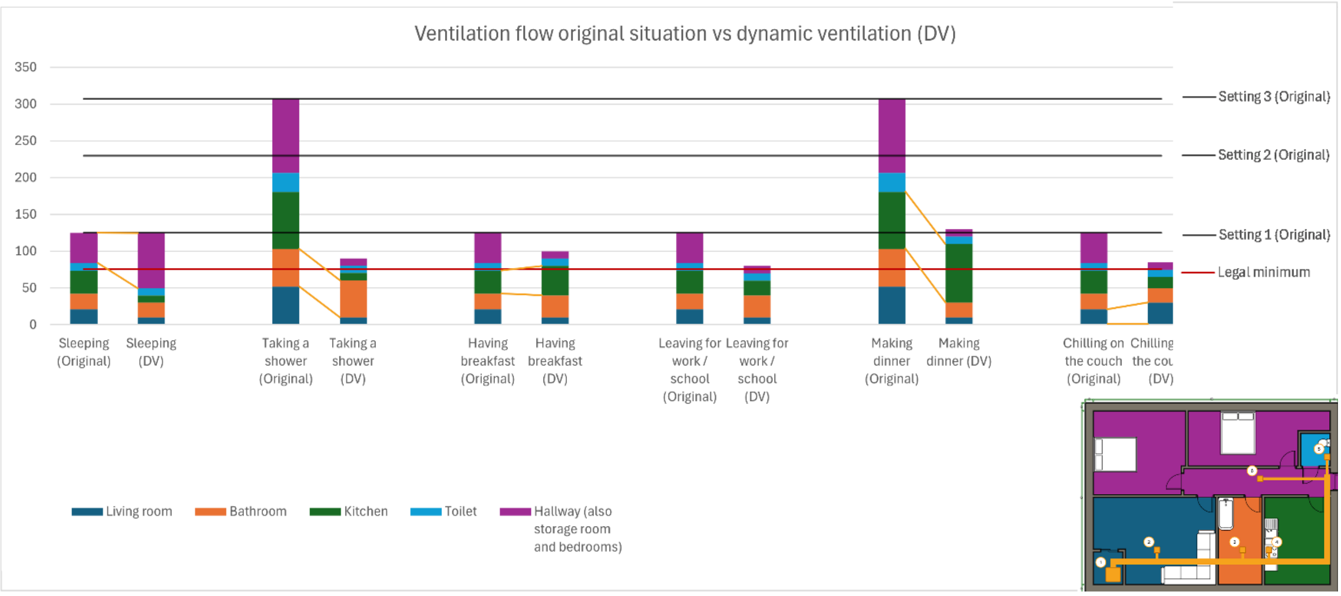


Figure E05: Visualisation of desired example scenarios

In Figure E05 a visual representation of the original and desired scenario is shown. It is interesting to note that most current ventilation systems do most likely not ventilate enough to keep all spaces at the healthiest air quality most of the time. The biggest differences between the original and dynamic scenario is that the ability to reach healthy ventilation levels in used spaces should be significantly better with dynamic ventilation.

Efficiency will most likely also be higher, although this might not be significant depending on your own daily schedule (Table E06). The total required ventilation is most likely lower than that required on maximum settings. As maximum settings were used for the dynamic ventilation scenario, total required flow of dynamic ventilation will most likely be much lower. This should be tested, however, will not be looked into further during this thesis.

Activity	Sleeping	Taking a shower	Having breakfast	Leaving for work / school	Making dinner	Chilling on the couch	Total	Required heating energy (kWh)
Time per day (h)	8	0.5	1	10	1	3.5	24	
Daily flow (m3/day) (Original)	1000	153.5	125	1250	307	437.5	3273	9.721082758
Daily flow (M3/day) (DV)	1000	45.2	100	800	130	297.5	2372.7	7.047116731
Heating bill saving with dynamic ventilation (DV)		*Ventilation≈43% of heating energy						12%

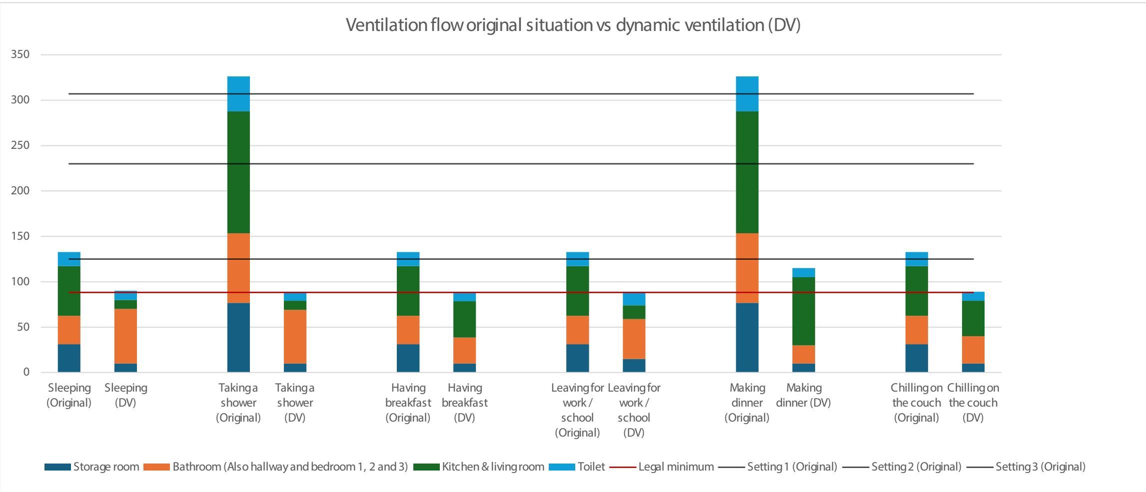
Table E06: Total daily flow for the example scenario 1

Example scenario 2 (Control scenario)

Situation with dynamic ventilation									
Living area	Size (m2)	Valve type	Required possible ventilation	Sleeping	Taking a shower	Having breakfast	Leaving for work / school	Making dinner	Chilling on the couch
Bathroom (Also hallway and bedroom 1, 2 and 3)	16	Active	50.4	60	59	28.5	44	20	30
Bedroom 1	16		40.32	20	19.66667	9.5	14.66667	6.666667	10
Bedroom 2	14		35.28	20	19.66667	9.5	14.66667	6.666667	10
Bedroom 3	16		40.32	20	19.66667	9.5	14.66667	6.666667	10
Hallway / stairs	15		37.8	60	59	28.5	44	20	30
Kitchen & living room	35	Active	88.2	10	10	40	15	75	39
Toilet	2	Acgive	25.2	10	10	10	15	10	10
Storage room	20	Active	50.4	10	10	10	15	10	10
Total minimum	88.2	-	88.2	88.2	88.2	88.2	88.2	88.2	88.2
Total	73	-	214.2	90	89	88.5	89	115	89

Original situation									
Living area	Size (m2)	Valve typ	possible	Sleeping	shower	breakfast	work /	dinner	the couch
Bathroom (Also hallway and bedroom 1, 2 and 3)	16	Passive	50.4	31.25	76.75	31.25	31.25	76.75	31.25
Bedroom 1	16		40.32	10.41667	25.58333	10.41667	10.41667	25.58333	10.41667
Bedroom 2	14		35.28	10.41667	25.58333	10.41667	10.41667	25.58333	10.41667
Bedroom 3	16		40.32	10.41667	25.58333	10.41667	10.41667	25.58333	10.41667
Hallway / stairs	15		37.8	31.25	76.75	31.25	31.25	76.75	31.25
Kitchen & living room	35	Passive	88.2	54.6875	134.3125	54.6875	54.6875	134.3125	54.6875
Toilet	2	Passive	25.2	15.625	38.375	15.625	15.625	38.375	15.625
Storage room	20	Passive	50.4	31.25	76.75	31.25	31.25	76.75	31.25
Total minimum	88.2	-	88.2	88.2	88.2	88.2	88.2	88.2	88.2
Total	72	-	201.6	125	307	125	125	307	125

Notes	
Occupants	4
*Total minimum is determined by the ventilation capacity of the biggest ventilated space. So it does not need to be the total sum of all	
*Unless otherwise indicated, values are in m3/h	
*Rooms without valves are ventilated passively by flow through other rooms. In this case it is assumed the hallway valve flow attracts that flow	
*Constant will most likely fluctuate with +-6 depending on total ventilation request. When passive valve further has lower flow, the maximum value of the passive valve will be taken into account	
*In houses without 2 way ventilation, natural ventilation will occur slightly, and therefore contribute to the total ventilation value. This	
*The values of these datapoints are estimated based on one room being used at any time for dynamic ventilation, and the ventilation settings only changed by the user when cooking or showering for the original situation	



Activity	Sleeping	shower	breakfast	for work /	dinner	on the	Total	heating energy
Time per day (h)	8	0.5	1	10	1	3.5	24	
Daily flow (m3/day) (Original)	1000	153.5	125	1250	307	437.5	3273	9.721082758
Daily flow (M3/day) (DV)	720	44.5	88.5	890	115	311.5	2169.5	6.443595797
Heating bill saving with dynamic ventilation (DV) *Ventilation=≈43% of heating energy								14%

Figure E07: Total daily flow for the example scenario 2

Appendix F – Sensors

Reasoning behind sensor choices, desired sensor response, system response and sensor cost.

What is the problem?

Controlling air quality more accurately will be done by adapting the area (m^2) in the valves air can pass through. This will change the ratio of flow to different valves, allowing increased ventilation to only take place in set areas. To determine where increased ventilation is required sensors are required. However, what type of sensors, where they should be placed and what effect their signal should have on the system needs to be discussed further.

What types of sensors are there?

To measure air quality a lot of different substances can be measured, of which the attribute for measuring the most important ones are indicated in Table F01.

Substance measured	Cost	Energy use	Relevance	Note	Suitable for project?
Carbon dioxide (CO_2)	High	High	High	CO_2 is a reliable and quick indicator for ventilation needs	Yes
Particulate matter 2.5 ($PM_{2.5}$)	High	Medium	Medium	Primarily problematic in houses without HVAC system	Low
Particulate matter 10 (PM_{10})	High	Medium	Medium	Primarily problematic in houses without HVAC system	Low
Ozone (O_3)	Very high	-	Low	Quantity originating in-house minimal	No
Nitrogen oxides (NO_x)	Very high	-	Low	Quantity originating in-house minimal	No
Carbon monoxide (CO)	High	Low	Medium	Might be interesting to promote safety as added benefit. Unclear or multiple sensors are beneficial	Optional
Sulfur diocide (SO_2)	Very high	-	Low	Quantity originating in-house minimal	No

Table F01: Types of substances, relevant for health and their relevance to the project (Ma et al., 2020) (Murena, 2004)

For the health aspect of this project a CO_2 sensor is a must. Together with relative humidity (rh%), CO_2 is used industry wide as standard for measuring ventilation need. As CO_2 sensors are expensive, many companies use eCO_2 values, measured by VOC sensors to estimate CO_2 values. However, these sensors are not accurate and usually are required to be zeroed outside. An alternative sensor is a nondispersive infrared (NDIR) sensor. Which is slightly more expensive, but much more accurate. KlaasJan Veltman recommended to use one from a product he knew to work well. Which uses Cubic's CM1106SL-N super low power consumption NDIR CO_2 sensor (Low Power HVAC system Small CO2 Sensor | Cubic CO2 Sensor).

As an optional extra it might be interesting to offer a variant with a CO detector installed. Installing these sensors/alarms integrated avoids maintenance and keeps the ceiling clean. The detection requirements are similar to that of a rh% sensor, meaning they could be placed next to one another. Giving a double function to the system, and a premium variant to offer clients for sales.

Apart from substances relevant to health, there are also values relevant to the feeling of comfort and/or to keep the house's condition in tact (Figure F01).

Value	Cost	Energy use	Relevance	Note	Suitable for project?
Temperature (°C)	Low	Low	High	Associated by users as the primary value to indicate comfort	Yes
Relative humidity (rh%)	Low	Low	High	Mainly useful for bathroom and kitchen	Yes
Flow (m^3/h)	High	Medium	High	Useful to meet minimum ventilation requirements	Medium

Table F02: Values relevant to the feeling of comfort and/or the house's condition (Appendix B) (Column-het-belang-van-goede-inregeling, 2019)

Although not directly applicable to the necessity to ventilate, temperature can be used in the future to guide alternate BEN system products (e.g. area-specific heating) or guide temporary decrease to minimum ventilation requirements when a space needs to be heated quickly to reduce energy consumption.

Relative humidity (rh%) is the second value used industry wide to measure ventilation requirements, primarily to avoid the growth of mould. Primary sources of increased humidity are showers/baths and humidity escaping whilst preparing food. In a ventilation heat-pump using the humid, often warm, air can majorly increase efficiency of the ventilation heat-pump itself (P. van Oostrom, personal communication). Therefore, the ability to concentrate increased ventilation to these areas is even more useful.

Flow is also measured in the BEN. Minimum ventilation requirements can be met by only measuring it in the BEN ventilation heat-pump (Appendix E – Desired ventilation behaviour (Is this allowed?)). Therefore, sensing this at a valve is not necessary.

Are sensor readings impacted by flow?

Yes they are, however, they can be covered to reduce impact. This was tested with the Resideo air quality sensor. Which uses the same CO_2 sensor that was recommended to me by the company. During the test the sensor was covered in a variety of ways, and placed into the end of an airduct. The flow volume was then changed to see if this impacted the data shown by the sensor (Figure F03).

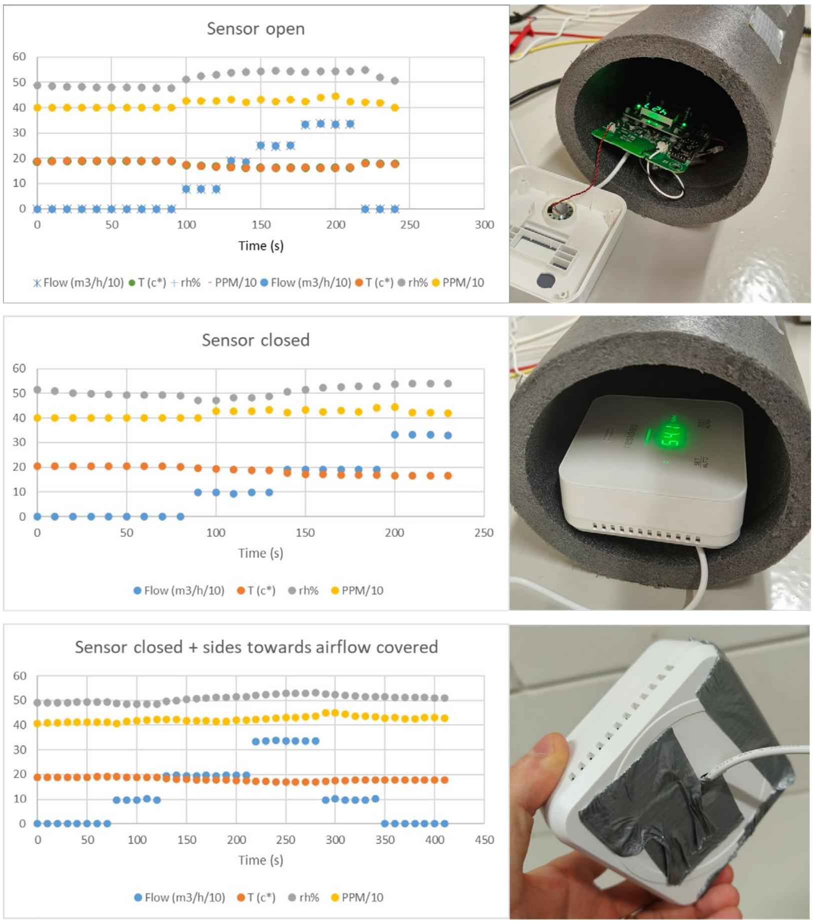


Figure F03: Impact of flow on sensor test data (ppm indicates CO_2 density)

The test has shown that for CO_2 and humidity a higher concentration is measured, when flow is increased. The system could possibly mistake this for a fast growing value. The effect can be lessened by partially covering up the sensor, which needs to be done anyway to avoid dust related miscalculations / damage.

When this is done both CO_2 and rh% remain well within the acceptable error range in which they sare still useful to operate (P. van Oostrom, personal communication), especially when is taken into account that airflow through each valve should not exceed 80m^3/h (Appendix B).

When and how to react to sensor signals?

Although valves will measure sensor values, the BEN will control required actions, as BEN will be used as a hub for the BEN system. Meaning data from different products could be shared to improve others. Furthermore, future updates and improvements can then be directly implemented into the BEN, without requiring updates for the valves. This means that data traffic will look as follows:

Value in room > Measured by valve > Send to BEN > BEN determines action > BEN requests valves to ‘Open up’/’Stay in position’/’Close’/’Go to 0 position’ (Appendix G – User interactions (System installation)).

For each sensor type the required operating range, and preferred reading can be seen in Table F04.

Sensor type	Low range	Acceptable range	High Range	Unhealthy / uncomfortable
CO_2 (ppm)	None	500-1000	1000-1500	>2000
rh% (%)	0-40	40-50	50-65	>70
Temperature	Used when outside temperature is more desirable (Not properly explored)			
*The system's response to rh% is also dependent on outside humidity				

Table F04: CO_2 and rh% range categories (P. van Oostrom, personal communication)

The BEN ventilation heat-pump will always be the one steering the system. Desired system response to different signal strengths can be found in Table F05. When a valve is at their most closed setting. It is important that in the most closed position the valve still allows air to flow through, so sensor readings remain up to date.

Priority	Situation	Total ventilation	Valves
1	All signals high	Maximum (350 m^3/h)	Go to 0 position (Appendix G)
2	1 or more signals >high	Maximum (350 m^3/h)	Fully open >High valves. Close all that acceptable or low
3	1 or more signals rise to high within 1 minute	Quickly increase	Close all that acceptable or low
4	1 or more signals high (In max. open position)	Increase	Slowly close valves that are in lower half of acceptable range
5	1 or more signals high (Not max. open position)	Don't change	Slowly open high valve, slowly close low and lower half acceptable valves
6	All signals low or acceptable	Don't change	Close low valves
7	All signals low or lower half acceptable	Minimum (77)	Open all valves that are acceptable to 0 position (Appendix G) close all low valves
*In this table signal refers to the measured level of CO_2 and/or rh% in 1 valve *Ventilation speed increase is determined by the highest relative position in high range of CO_2 or rh% *Minimum ventilation requirement is 75.6 m^3/h for all family houses without a room >30m^2 (Appendix E)			

Table F05: Proposed order of signal importance

Setting the requirements as formulated in Table F05 would make the system complex to program. To simplify the program, the opening distance of each individual valve would be determined by the acceptable range and the total system ventilation by the high range (Table F06). The two remaining exceptions are when all valves request high flow or all valves request low flow. In these cases the valve positions return to the 0-position.

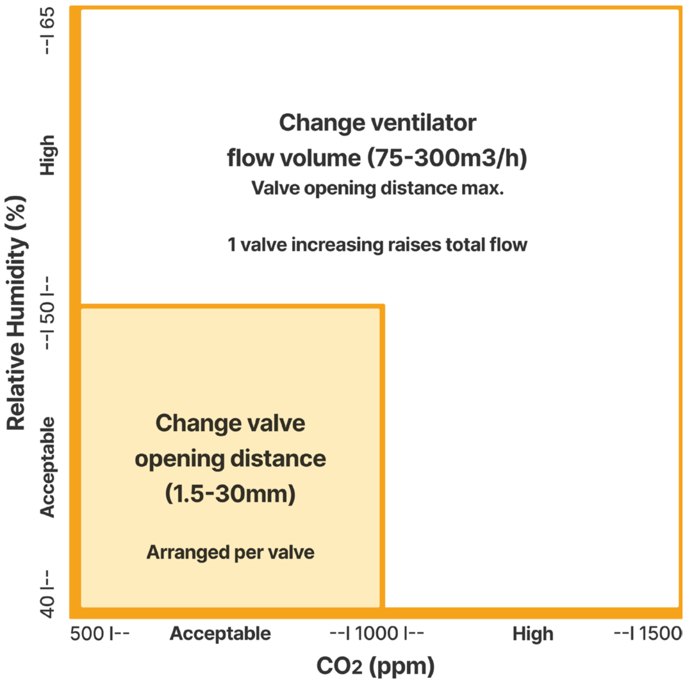


Table F06: Proposed system reaction to sensory values

An extra exception, which has not properly been explored, is the use of the temperature sensor to steer ventilation when outside temperature is more desirable. For example, during summer in the Netherlands a lot of heat is stored in houses. When outside temperature is colder than the temperature of certain rooms, this temperature difference could be used to steer ventilation towards areas most heat is stored. As the presence of CO_2 indicates the presence of people, these areas (e.g. sleeping rooms) could be prioritised to further increase comfort.

Wired vs battery powered

If the system can be ran wireless is dependent on the type of CO_2 sensor and if a CO sensor is attached. When a NDIR or CO sensor is used, the system must be plugged into the power grid. If a CO sensor is not installed and an VOC sensor is used. The system could be used for 1,5 years without changing the battery, whilst using 1 AA battery. As a CO sensor does not influence the primary goal of the system, it will not be taken into account for choosing how the system will be powered.

When using a system that is plugged in wires would need to be fed through the wall/ceiling or attached onto them. It might also be possible to run the wire through the ventilation tubes. If this is done they'd need to be designed to withstand tube cleaning, which will be difficult. Running the wires through the tubes would be advantageous as it would minimize the amount of adapters required to power all valves to 1. Which would save €12,- per adapter.

Apart from practical reasons, making the system wireless would also be advantageous for certification. Using low voltage and making the product battery powered would decrease certification requirements, certification costs and production cost.

Price

Costs are dependent on the type of CO_2 sensor. Currently Joule is testing if a VOC sensor is accurate enough for their thermostat. These results could be used to determine if a VOC sensor is accurate enough for the dynamic ventilation system. Costs for different scenarios are displayed in Table F07. When quantity becomes much higher than 3000 pieces, prices are expected to reduce by 20%.

Type of CO_2 sensor	Power supply	Price (€)
VOC	Wireless	30-35
VOC	Wired	40-45
NDIR	Wired	50-60

Table F06: Total electronic cost per scenario with a production quantity of 3000 pieces

Appendix G – Desired product interaction

Product use cycle

What is the problem?

During the product's lifetime different stakeholders will come into contact with the product, all with different requirements. To maximise the understanding of the requirements necessary to the product's success, a partial lifecycle analysis was made (Figure G01). We'll discuss different parts within the use phase to find requirements and new insights on dynamic ventilation.

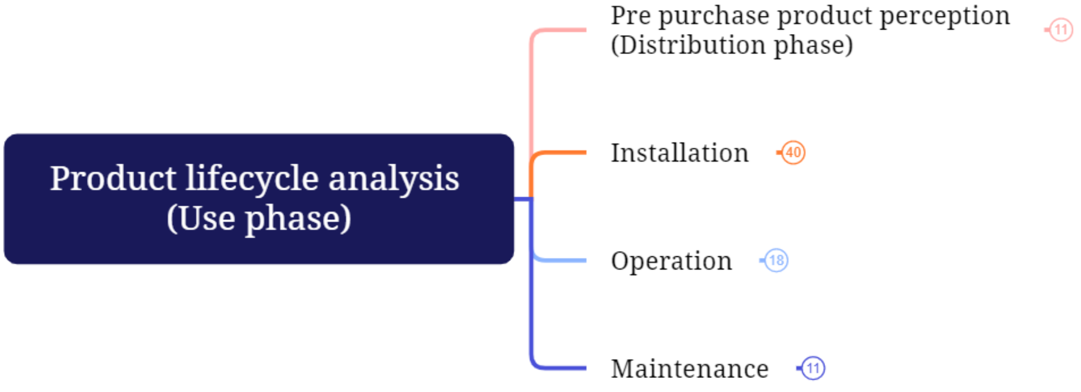


Figure G01: Most important branches of the product lifecycle analysis for dynamic ventilation.

Pre-purchase product perception

Why should should someone invest in this extension? What impression should be given to potential buyers? How should the product me marketed (Figure G02)?

For most homeowners / developers cost and legality are the thriving factors for investing into alternate climate systems (2. Context). Legality is interesting for new houses, however this project is aimed at existing houses, making ROI the most important factor. Dynamic ventilation achieves this by reducing the amount of air that needs to be heated / cooled, so occupants can save money on their energy bill (Appendix E). This should be communicated to potential buyers.

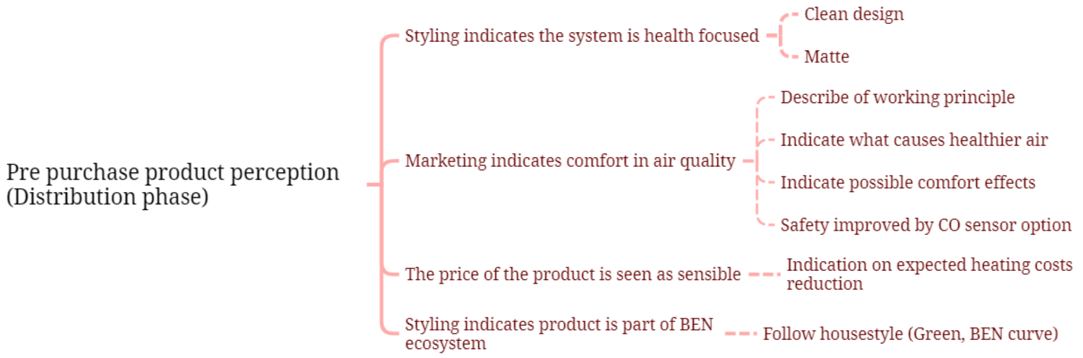


Figure G02: Lifecycle analysis, product perception

This product will be part of the BEN ecosystem lineup, and incorporate the same principles BEN is targeting. Health and comfort are important factors. This is what dynamic ventilation was designed around, optimizing the amount of CO_2 and humidity for each area (Appendix E). This clean and healthy experience should be emphasized by the product. Visually the impression of health can be strengthened by creating a 'clean' smooth and simple design. This could be further strengthened by using a matte finish, as this doesn't get visually dirty quickly and creates a more classy appearance (Figure G03). A matte finish also makes the object less prominent in the room in the use phase.

Figure G03: Colour and texture example. From left to right, Shiny white, matte white, matte graphite

Installation

With the installers being important stakeholders, this is an important phase. Where do we install the system? How can we make this process more streamlined and convenient for the installer? As this is a big phase it is segmented into 3 main topics (Figure G04).

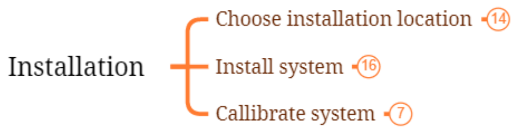


Figure G04: Lifecycle analysis, Installation

Choosing installation location

This project aims to replace used valves in houses with existing ventilation tubes. This is advantageous as installing tubing can be expensive, takes time and effort. Using existing infrastructure also means you're bound to its limits (Figure G05). Different types of tubing exist, but the inner diameters are standard. Most current valves use small plates as springs to keep themselves locked inside a tube. To keep the dynamic valves in place these springs or the seal can be used. The valve can in most cases extend up to 7 cm into the tube (Personal communication, K.J. Veltman, 2025), however it'd be beneficial to lessen the required space so it can be used in more situations.

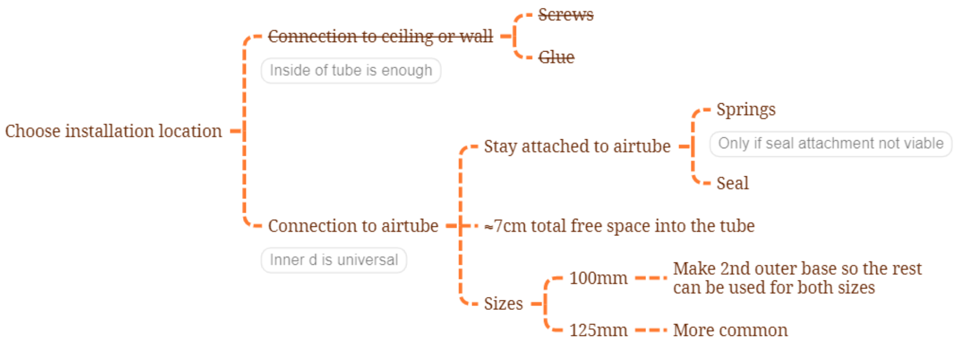


Figure G05: Lifecycle analysis, Installation, Choosing installation location

Although inner diameters are standard, different ones exist. The most common size in target houses has a 125mm diameter. 100mm diameter versions also exist, mostly in older installations (Appendix B). It might be useful to design the regulation-body to be 1 size suitable for 2 different outer-bodies, so both types of tubing can be regulated.

Installing the system

Installing the systems could be done by following the steps in Figure G06. For pairing and system resets a button should be added to the valve. The button does not need to be accesible whilst the valve is placed in the tube. To finalise installation, an extention should be made for the installer / maintenance app, so valves can be connected to the BEN and adjusted accordingly. If part of these settings should be accecible to the user's app should be alligned with the app settings of the BEN heat-pump. However, by allowing users to change settings within a reasonable margin, the feeling of control and system understanding could be increased for interested users.

Allowing for a range of settings to be changed per room can also have advantages for system efficiency. For example, asking installers to choose a room type or allowing users to create custom rooms, could allow valves to be callibrated differently to different environments (e.g. More often measuring humidity spikes in the bathroom). When more data is gathered through use, these settings can then later be updated through updates for the BEN. Increasing airquality for users.

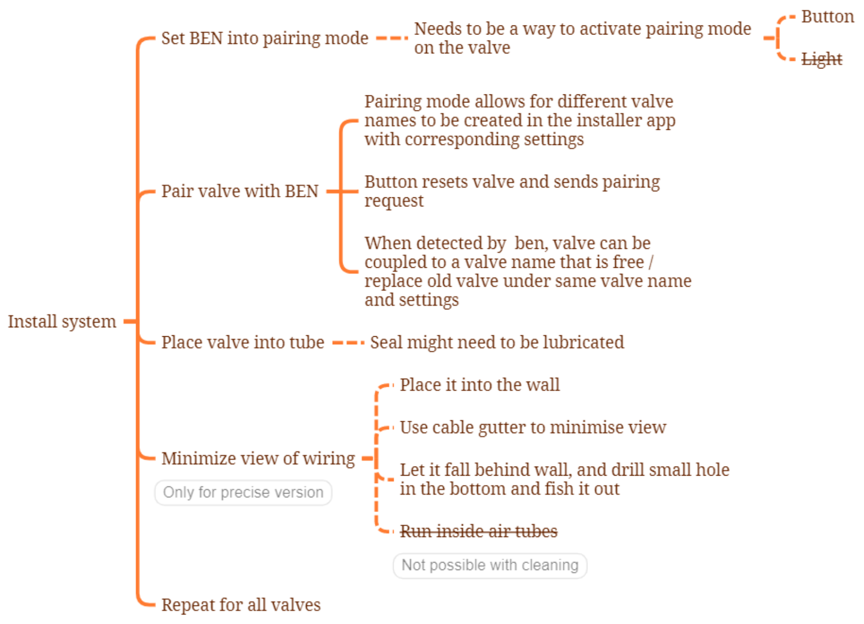


Figure G06: Lifecycle analysis, Installation, Installing system

Due to building regulations for new houses possibly requiring more precise measurements, the system might need to have a version that is connected to the power-grid (Appendix F). In some houses this can be preinstalled. However, in houses where the system is implemented after, wiring will have to be installed and hidden. Preferably through the ceiling or wall without breaking it open. However, this is not always possible. Installing wiring, for example in concrete, can be costly. Alternatively small adhesive cable ducts could be used, although they influence the room's look.

Callibrating the system

Calibrating HVAC systems is currently done by opening all valves, setting the system to maximum flow. Then closing them by hand, until the flow measured by the installer matches the legal minimum of each room (Appendix E). Dynamic valves should follow the same procedure, however, opening and closing is done through the installer application. Also, flow should be slightly higher than the legal minimum to minimize total system resistance (Figure G07). This data should then be saved as the 0 position for each valve. Most normal valves have an indicator that shows the valve's setting. This setting could be used to adjust all valves without the need for the installer to come and measure flow per valve.

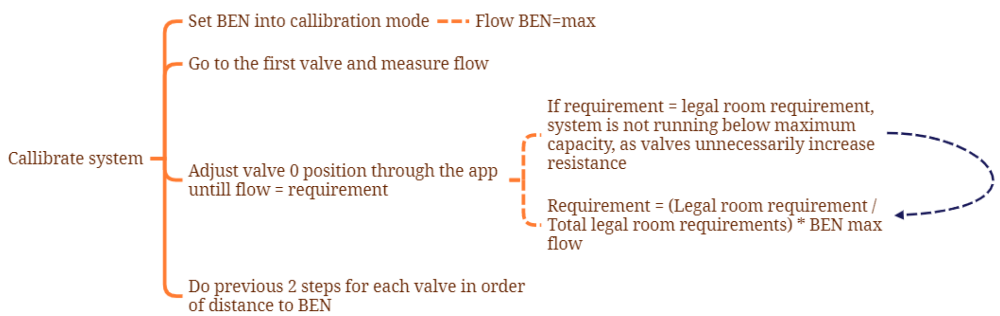


Figure G07: Lifecycle analysis, Installation, Calibration

Operation

Whilst in use, the system should undertake most steps by itself (Figure G08). During this time users are the only stakeholders in direct contact with the system. Users are generally not interested in actively adjusting the system, although, they do wish to understand what is happening (Appendix B). In other words, to be informed. During this project the choice was made to do this by showing the user system movement. Using the closing mechanism of the dynamic ventilation valves to show what the system is doing. Kind of like the house is breathing.

Informing the user could be strengthened by adding a differently coloured surface on the inside, that shows when the valve opens (Figure G09). It makes the valve stand out more, which from personal conversations, doesn't seem to be desirable. However, this would be during a moment the user should be informed the system is working and could help with brand recognition.

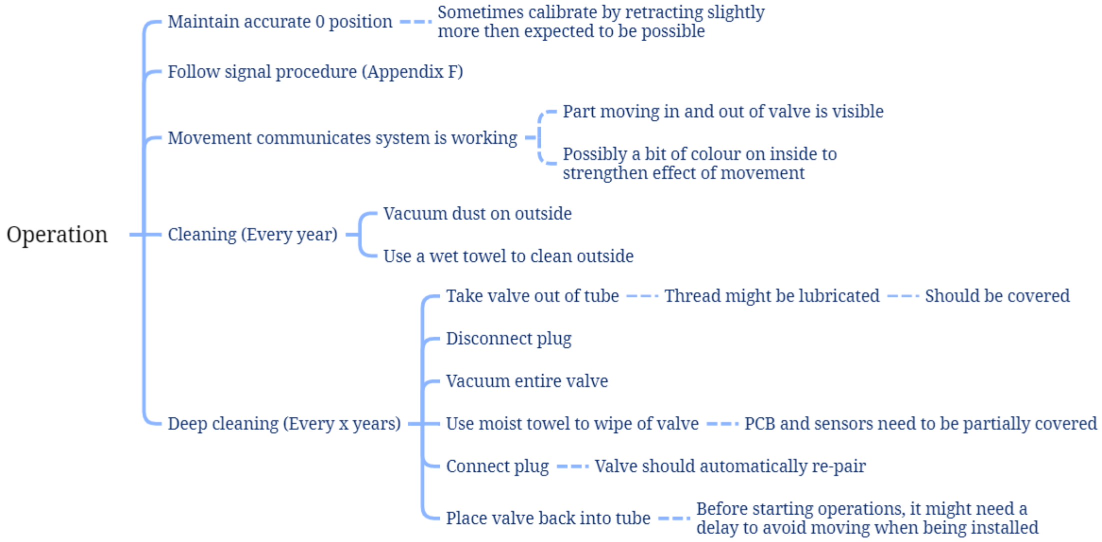


Figure G08: Lifecycle analysis, Operation

Figure G09: Comparison of fully extended valve with or without colour

To keep the resistance low and sensors working, dynamic valves should be cleaned in regular intervals. The assumption was made that this should be done once or twice a year, as is the case with current valves. In the future, the required amount of intervals should be tested. This test / evaluation should also clarify if every clean should be a 'deep clean' (Figure G08). Or if having a cleaning setting in the app, where valves extend fully, provides enough accessibility to keep the valves in good condition.

Cleaning on a yearly basis also provides a good moment to switch out the AAA batteries. The batteries are expected to last 1,5 years (T. van den Berg, Personal communication), warning the user to clean and replace them after just over a year would ensure a grace period. If a valve's power level is deemed too low, the empty valves should return to their 0 position. If this happens to too many / crucial valves, the system returns to a normal passive valve system. What is too many / crucial should be tested if the project is continued.

Maintenance

The BEN communicates with Joule's servers to log the state of different sensors. This is meant to improve systems in the field with updates and to allow for preventive maintenance. The BEN could also do this for dynamic valves, logging errors, loss of contact and possibly motor stall. These values could be used to give the user warnings about required cleaning or upcomming maintenance. For housing corporations these warnings can streamline maintenance and lower total maintenance cost (Figure H10).

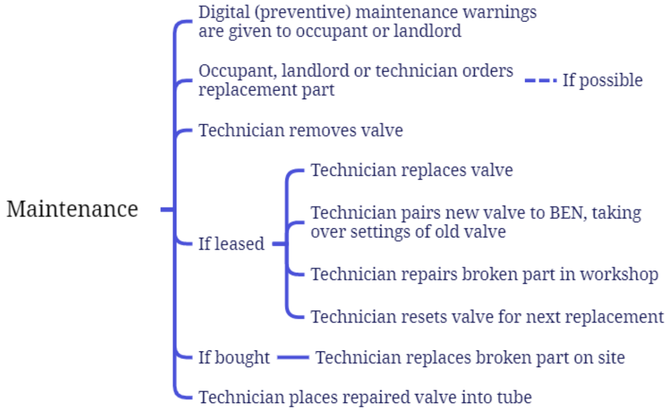


Figure H10: Lifecycle analysis, Maintenance

As heating installations often come with maintenance contracts, adding the BEN and / or the BEN system to a similar contract might be beneficial as preventive maintenance can proactively be performed. This can also be taken one step further, providing the system in a product as a service model. For housing corporations maintenance contracts could be advantageous for recuperating the investment through the contract over time.

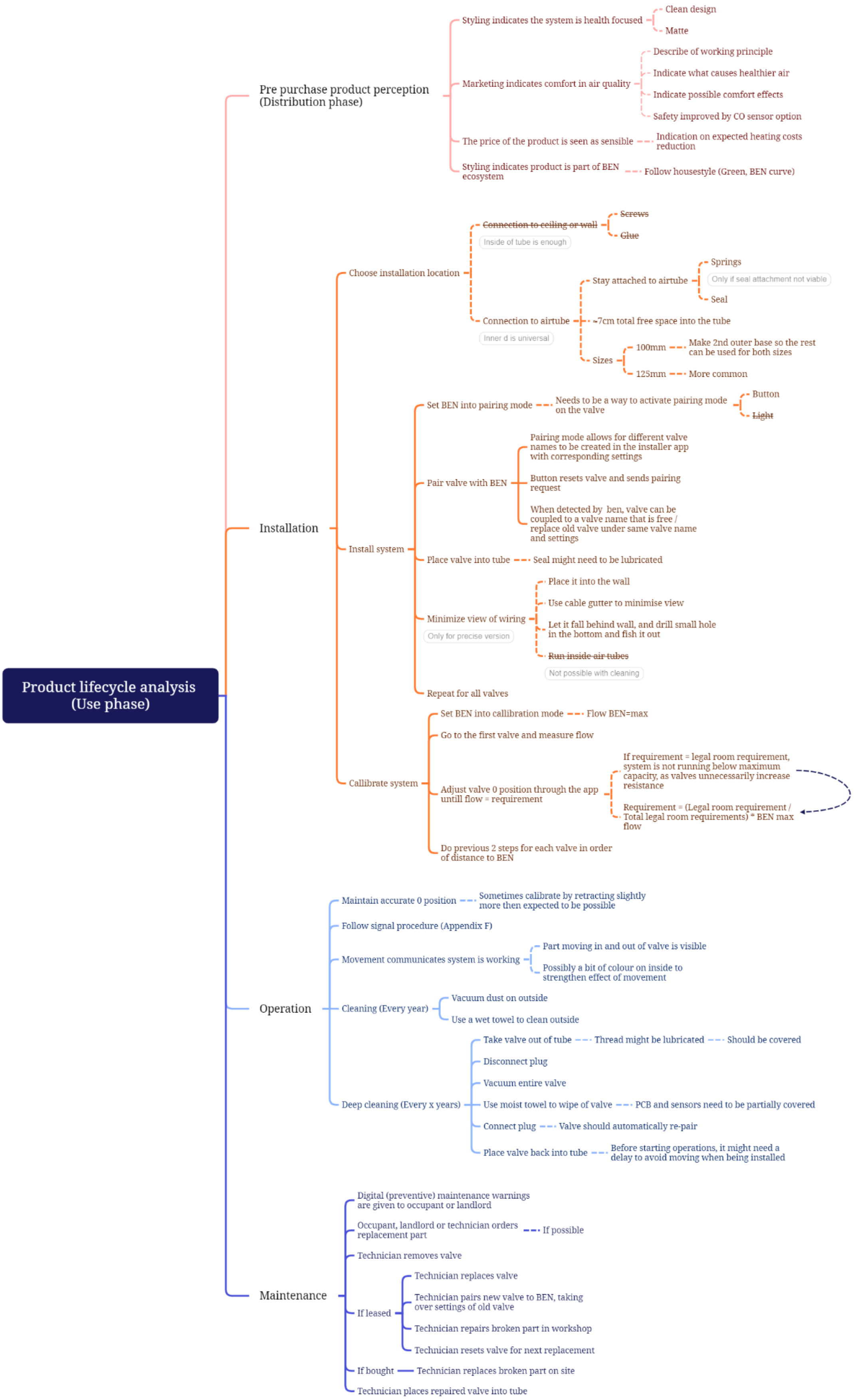


Figure H11: Lifecycle analysis

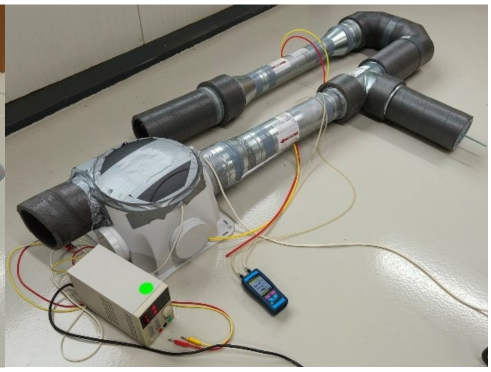
Appendix I – Test setup

Visuals and layout of testsetups

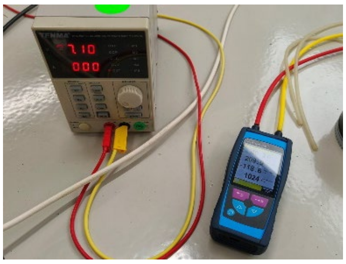
What to test?

In order to compare future prototypes and to test the final version, a test set-up with two setup orientations was created. Both can measure flow and pressure differences in different areas.

1. Single valve setup. Made for direct pressure difference testing with one valve.
2. Double valve opening setup. Made for testing different valves, and their response to each other in all required situations according to Appendix E.

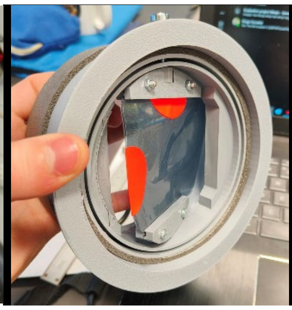


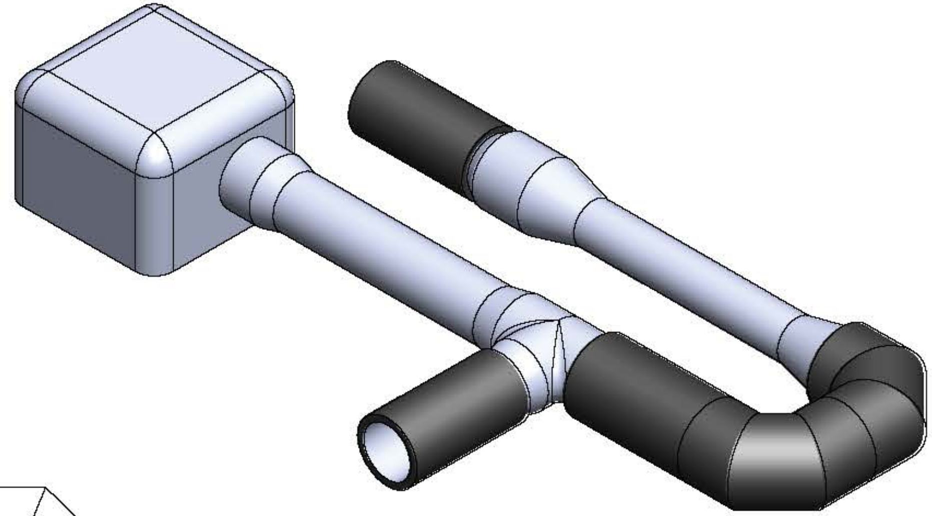
How does it work?

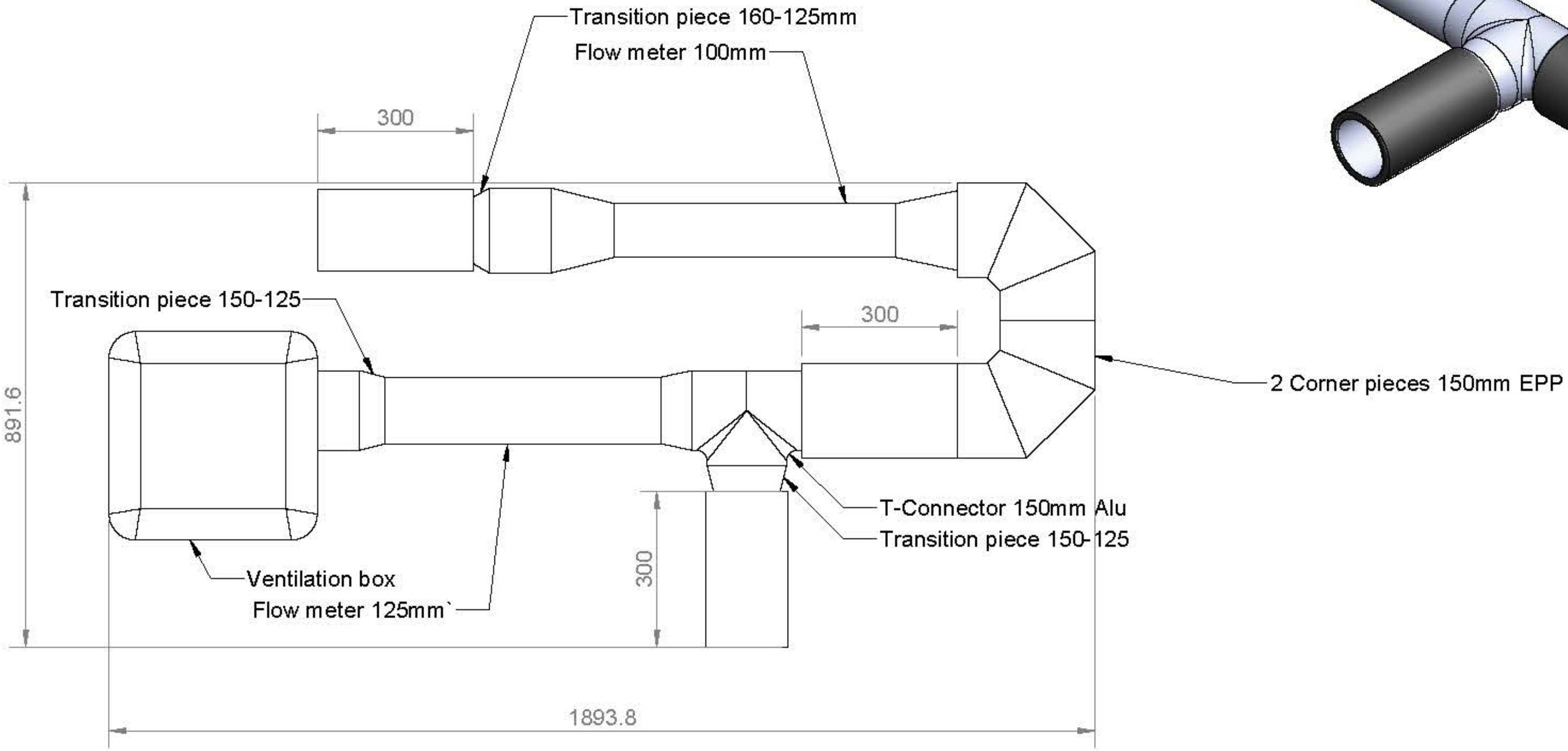


The setup is powered by the ventilator, which can be controlled by giving it a signal from 1-10v, currently done by the bench power supply. A pressure difference sensor is used to monitor the differences in pressure, either in the outside air against the inside tube pressure, or the pressure difference in the flow measurement tube vs the air catcher valves in the same tube. The later two can be used to calculate flow speed.

The test setup has 125mm tube endings in which to test prototypes for different types of valves like the ones shown underneath.







PART LIST
AERFOAM
3x tube 300mm (Tube length may be changed if more convenient)
2x corner piece 150mm
ALUMINUM
1x y-piece (Needs to be bought, not available in lab)
1x flow meter 125mm
1x flow meter 100mm
1x transition piece 160-125mm
2x transition piece 150-125mm
OTHER
1x ventilation box
1x aerfoam conntection clamp

Scale: **1:10** Units: **mm**
Projection: Check:
General tolerances unless otherwise specified according to DIN ISO 2768 m.
All deliverables need to be according the latest RoHS, reach and other applicable directives such as the drinking water directive.
Remarks:
Material:
Material <not specified>
Description:

joule Technologies

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